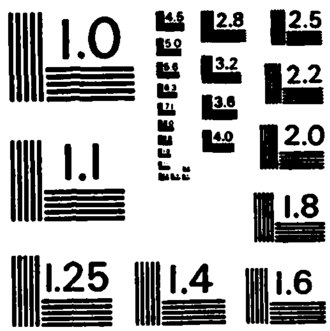
AD-A121 528 TEST AND EVALUATION OF CGC POLAR STAR WAGB 10 VOLUME III BACKGROUND(U) NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY NSTL STATION MS J P WELSH SEP 78 1/1

UNCLASSIFIED NORDA-22-VOL-3 MIPR-Z-51100-8-0003 F/G 13/10 NL




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

NORDA Report 22

(1)

# TEST AND EVALUATION OF CGC POLAR STAR WAGB 10

## VOLUME III BACKGROUND


JAMES P. WELSH, JR., EDITOR

Polar Oceanography Branch
Oceanography Division
Naval Oceanographic Laboratory


September 1978



Prepared for:
Coast Guard Research
and Development Center,
Groton, CT.

Approved for
Public Release




NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

# TEST AND EVALUATION OF CGC POLAR STAR WAGB 10

## VOLUME III BACKGROUND

JAMES P. WELSH, JR., EDITOR

Polar Oceanography Branch
Oceanography Division
Naval Oceanographic Laboratory

September 1978

Prepared for:
Coast Guard Research
and Development Center,
Groton, CT.

Approved for
Public Release

NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

## FOREWORD

CGC POLAR STAR is the first of a new class of American icebreakers built for and operated by the U.S. Coast Guard. The vessel's design incorporates many new and sophisticated systems not found on earlier icebreakers.

The primary objective of the test and evaluation program was to examine the performance characteristics under actual polar operations. Two field trials were conducted. The first in the Arctic (Appendix A) and the second in the Antarctic. During these field trials approximately 120 individual parameters were measured and recorded on magnetic tape (Appendix B). Additionally, the physical properties of the sea ice in which the ship was operating were measured.

Documentation of the complete program including preliminary screening of the data has been accomplished by NORDA under contract to the Coast Guard Research and Development Center. The documentation consists of the following four volumes: I. Antarctic trials, II. Test Plans, III. Background, and IV. Instrumentation Manual.

# EXECUTIVE SUMMARY

Section I is a description of the POLAR class vessels. The description was prepared by excerpting the work of various individuals, including CWO V.B. Midgette and LCDR T.E. Braithwaite and the Welcome Aboard Pamphlet. This information has been published elsewhere in Coast Guard documents but is reproduced here for ready reference.

Section II through VI are the work of CDR G.P. Vance, USCG. During the summer of 1975 CDR Vance attempted to predict the icebreaking performance of the POLAR class vessels prior to their first use in the ice. This was done to assist in the development of the icebreaking test plan for these vessels. He based his predictions on the results of the various equations and theories available in the literature at that time. Vance evaluated the adequacy of these equations and theories by comparing the results of other classes of icebreakers to the actual performance of those vessels. The magnitude of measurement errors for various parameters and physical properties during the testing were estimated to determine their impact on the precision of the overall test results.

Ralph R. Goodman

RALPH R. GOODMAN
TECHNICAL DIRECTOR
NORDA

CONTENTS

Page

Page

APPENDICES

## LIST OF ILLUSTRATIONS



## LIST OF TABLES

## I. GENERAL COMMENTS ON POLAR STAR

The USCGC POLAR STAR (WAGB 10) is the first new icebreaker to be built for the United States since 1954. The Lockheed Shipbuilding and Construction Company of Seattle, Washington, built the POLAR STAR and is presently completing her sister ship, USCGC POLAR SEA (WAGB 11). Eventually these two ships will operate out of a support complex located in their home port of Seattle, Washington.

POLAR STAR's design resulted from three years of research and testing. The design incorporates a number of improved and innovative features that affect nearly every aspect of her operation. Much of the equipment installed aboard is highly sophisticated such as the propulsion control system and electronic navigation equipment. There are three computers, one for monitoring engineering machinery, one for handling oceanographic data, and one for navigational capabilities. In keeping with current technology and the desire to reduce manpower requirements, automation fulfills functions to a degree unprecedented in the Coast Guard.

The hull shape for POLAR STAR is derived partially from studies made by Capt. Roderick M. White, USCG, whose ideas were incorporated into the bow design of the icebreaking tanker MANHATTAN. Basically, the hull is configured to maximize icebreaking capability through the combined forces of the ship's forward motion (as it rides up onto the ice) and the downward pull of gravity.

The shell plating and support structures are fabricated from A-537 steel having chemical and mechanical properties which can withstand heavy impacts and loading at low temperatures. Essentially three different types of steel have been used in the construction of the ship (A-537, HY-80 and A-131). The icebelt plating in the forward and after portions of the hull is 1 3/4" thick. This shell plating thins down to 1¼" amidships. Portions of the hull that are above the waterline and clear from ice are ½" thick.

The propulsion system centers on a diesel-electric/gas turbine plant that powers three shafts. The diesel generators supply AC electrical power which is rectified for the DC propulsion motors. The gas turbines are coupled via a reduction gear directly to the shaft. Either the diesel-electric or the gas turbine mode of operation can be used, but not both together. The diesel-electric units produce a total of 18,000 continuous shaft horsepower and are the normal mode of propulsion. The gas turbine units produce a total of 60,000 continuous shaft horsepower for especially heavy icebreaking or emergencies. Due to the turbines' higher rate of fuel consumption, they will be used sparingly.

The propulsion machinery is spread over five separate compartments. The forward two compartments house diesel generators, supplying electricity for propulsion and shipboard use. The third engineroom aft contains the gas turbines. The after two compartments contain reduction gears and electric motors.

The three shafts (34" diameter) turn four-bladed, controllable pitch propellers having 16' diameters. This type of propeller permits almost instaneous control of the ship's direction of propulsion. Increased maneuverability is possible with this multiple shaft configuration. Additionally, the single rudder being mounted directly aft of the center line propeller will afford greater maneuverability than that of other U.S. icebreakers.

The shafts and motors are non-reversing and maneuvering control is obtained by adjusting the pitch of the blades on each propeller. The continuously turning shafts should be valuable during icebreaking as studies indicate an icebreaker's propeller is most vulnerable when stopped for reversing direction. With a controllable pitch propeller the need for reversing the revolution of the shaft is eliminated.

A computer controlled monitoring system keeps watch over the equipment in the engineroom. Selected machinery parameters are continuously scanned and recorded. If critical values are reached, the monitor system sounds an alarm and automatically secures certain equipment before permanent damage is done.

It is impossible to describe even briefly all of the equipment aboard POLAR STAR. However, the following items may be of special interest.

One innovation, as far as the Coast Guard is concerned, is the central hydraulic system which provides a single hydraulic power source for the entire ship. This avoids the necessity of generating the hydraulic power electrically at each individual machinery location. The 15 ton cranes aft and 3 ton crane forward, for example, are both operated off this central system.

There is a heeling system aboard utilized to rock the ship as an aid in freeing herself when stuck in ice. The system consists of three pairs of tanks connected by flumes with axial flow reversible pumps. Operated hydraulically, the pumps transfer the contents of each (approximately 35,000 gallons) or all three tanks to its mate on the opposite side of the ship. This is accomplished in 50 seconds generating 24,000 foot tons of torque on the ship.

Icebreakers are infamous for their heavy roll in the open sea. To dampen this effect a passive roll stabilizing system is installed. A continuous port to starboard tank is kept approximately 40% full of water. The placement of vertical pipes within the tank produces a nozzle effect to keep the "sloshing" water out of phase with the roll of the ship, thus tending to counteract the roll. The effect is a dynamic one, that is, it requires the ship to be rolling before it operates.

One special feature of POLAR STAR is the aloft conning station approximately 104' above the waterline. This platform provides a necessary valuable visual extension to the conning officer as he carefully searches for the best route through concentrated ice fields. Complete rudder and engine controls and necessary navigational devices are located in the station aloft. Access is via a ladder inside the mast.

An impressive amount of space has been devoted to scientific purposes. Five laboratories and offices as well as space for accomodating portable scientific vans have been included in the design. There is berthing for 10 scientists and technicians. The pride of the oceanographic instrumentation is the computer complex located in the ocean data center, which assures rapid reduction and assimilation of gathered data without the traditional delay until return to homeport.

The aviation capability is immediately apparent as the flight deck can land the heavy HH3F helicopter, but it is expected that two HH52A helicopters will make normal deployments with POLAR STAR. The helicopters are a vital tool to operating in the ice. They are the ship's "eyes" when difficult circumstances are encountered.

Perhaps the most notable feature of the USCGC POLAR STAR is her habitability. Careful consideration was given to the needs of the crew to insure they received the best possible in care and comfort. Duty aboard an icebreaker is long and can be arduous, especially when your ship is going to spend eight months a year deployed at sea. The manning requirements, for example, have been reduced to approximately 150, primarily through automation and the use of low maintenance materials. That number compares to about 190 for the older WIND Class icebreakers. The resulting extra space has been put to good use. Single, double and four man staterooms are provided for the entire crew. Sizable lounges, a library, a gymnasium and a soda fountain have been incorporated into the ship. Bright colors and modern decor contrast noticeably with the drabness of traditional color schemes. These and other points all contribute to the "livability" of POLAR STAR.

## II. COMMENTS ON VARIOUS METHODS OF EVALUATING AND/OR PREDICTING ICEBREAKER PERFORMANCE BY CDR G. P. VANCE

### A. Introduction

The current literature contains many references to the prediction of icebreaker performance. Some of the work is dated, some of the work is unique and some of the work has been vastly improved upon. This note will attempt to clarify the utility of each reference in the prediction technique, however, time does not permit presentation of each technique and sample calculations. Examples can be found in the references sited.

The prediction techniques can be broken down into several categories. Category one would contain the techniques that are analytical in nature and depend on knowing only the ship and ice parameters, i.e., no model tests or full scale tests data are necessary. Included in this category are predictions for continuous resistance in homogeneous ice, continuous resistance in slush ice, ramming capability and extraction capability.

The second category involves prediction techniques where model or full scale data are available for regression analysis to establish coefficients for the prediction equation. A discussion of the various techniques is contained in the following sections. A summary is contained in Table 1.

B. Category I

1. Discussion

Kasteljan (1968) formulated an equation that expressed ice resistance encountered by an icebreaker. Although his equation has some coefficients in it that have to be determined experimentally, the values published are taken as suitable for all hull forms. This is a source of some error in his technique. His equation takes the form:

$$Ri = k_1 \mu o B \sigma h + k_2 \mu o B \sigma i h^2 + k_3 \frac{1}{\eta_2} B^{k_4} V^{k_5} + R_4 \ ,$$

where: $k_1 = .004$
$k_2 = 3.6$
$k_3 = .25$
$k_4 = 1.65$
$k_5 = 1.0$

are determined experimentally and the other terms are explained in his 1968 paper.

The equation is cumbersome and is only accurate at low speeds (Vance, 1974). It appears to be outdated by the advance of technology and should only be used as a check. Details of its use are contained in Kasteljan's paper (1968).

White (1969) studied the downward force generated at the bow of an icebreaker and the effects that the bow shape had on this force. The assumption is that the icebreaker's capability is proportional to bow shape alone, which is not totally true. The performance is dependent on the entire shape of the vessel. Thus, this shortcoming permeates all of White's work. His equations should be used with extreme care, particularly the simplification to ice thickness broken for the application of a certain downward force.

Examination of White's equations show one limitation to the approach, i.e., it does not take into consideration the full ship. It should be used with extreme care as a check.

Milano's (1973) work does take into consideration all the ship's parameters as well as the ice characteristics. His solution is a complex algorithm that must be run on a computer. It has been my experience that the program does relfect what is happening for most icebreaking vessels. However, odd changes in shape must be analyzed with care. The current indications are that Milano's program yields results that are 10 to 15 percent lower than full scale results.

Table 1

Summary of I/B prediction techniques

| AUTHOR | YEAR PUBLISHED | REMARKS |
|---|---|---|
| CONTINUOUS HOMOGENOUS .CE | | |
| Kasteljan | 1968 | Too linear, low |
| White | 1969 | Not too accureate |
| Milano | 1973 | Low, needs comp. |
| Lewis | 1971 | Good at low speeds |
| Edwards | 1972 | Too linear |
| Enkvist | 1972 | Good at low speeds |
| Vance | 1974 | Good within 5 percent |
| CONTINUOUS SLUSH ICE | | |
| Milano | 1975 | Unproved |
| RAMMING | | |
| White | 1969 | Very approximate |
| Lewis | 1971 | Improved White |
| EXTRACTION | | |
| White | 1969 | Relative only |

### 2. Slush

Milano's (1975) program for slush ice is the only predictive tool available for such work. It was first presented in April 1975 and has not been field tested, i.e., used enough by design engineers to give confidence in the results. There is not much that can be said for its application to date; it must be tested to gain more insight into its strength and weaknesses.

### 3. Ramming

White (1969) developed a technique that yields an approximation of the thickness of homogeneous ice that can be broken in a ramming mode. Again his development is limited to the bow, which is more realistic in this case. Lewis (1971) has taken White's approach and made some improvements, particularly in the application of the downward force necessary to break the ice. The equations should be taken as approximates and are sensitive to the friction coefficient and bow angles.

### 4. Extraction

White's (1969) approach to extraction difficulty is a relative one and should not be used as an absolute indication of the ship's ability to extract itself with a given thrust. It is very sensitive to bow angle and one should be aware that he is referring to the bow angle at the end of impact rather than the bow angle at the designer's waterline. A detailed explanation is available in the report on ramming and extraction prediction by Vance (1974).

## C. Category II

Continuous homogenous ice:

The comments stated earlier pertaining to Kasteljan's equation apply here also. The coefficients in his equation are found through model tests or from full scale test data regression. His work although good in its basic concept is not precise enough for today's technology.

Lewis, in 1971, proposed an equation that appeared to be a good prediction but did not fit all shaped ships. It depended on model data to obtain coefficients in the equation.

Its difficulty lies in the fact that it does not contain the ship's length and the beam is not reflected in the breaking term. Lewis, et al., abandoned the equation in 1972 in favor of another equation (Edwards, 1972).

This equation has the inherent weakness of being linear in velocity which is contrary to most field data. It is a fairly good approximation at low speeds where the velocity effect is not predominant.

Enkvist (1972) used another regression technique that he felt was applicable to prediction of ice resistance. He did not include the length effect and his friction effect was ambiguous. His technique is complicated and requires several series of model tests to determine the applicable coefficients. His results appear to have the wrong slope for the resistance curve (Vance, 1974). In summary, I would not recommend Enkvist technique or equations for predicting full scale data.

Vance (1974) proposed a regression technique that included the length effect; however, because of the lack of any data to the contrary, he assumed the pressure effect was neutral, i.e., no adverse pressure fields existed. He also assumed that the friction effect was spread throughout all components and could not be separated out. His results were within 5 percent of full scale data.

It must be kept in mind that none of these techniques include the effect of pressure and are somewhat blase about the effect of friction, however,

that is the state of the art to date.

D. Summary

In summary, I would recommend Milano's approach for vessels that have not been model tested or are still on the drawing board. I would recommend Vance's approach for analyzing all model data.

## III. PREDICTED OPEN WATER PERFORMANCE CHARACTERISTICS OF THE POLAR STAR BY CDR G. P. VANCE

A. Abstract

The enclosed information will provide an estimate of the performance of the POLAR STAR in open water. The information is based on the Model Test Report P-223-H-09, "Powering Predictions and Flow Observations for the U.S. Coast Guard Proposed Icebreaker Design (M-14-3) Represented by Model 5245," by M.P. Lasky, L.R. Crook and P.B. Mathis, dated April 1971.

The RPM reported in the report may not be the RPM experienced in the field, therefore one should use care in computing the torque, i.e., each torque computation should be made using measured RPM.

One should also be careful in determing the power distribution when underway. The power distributed to the shafts is up to the operator and may not be equal, however, the total power should be equal to the figures presented herein. (See Table 2 and Figs. 1-2).

B. Basic Equations

$$IHP - \frac{PLAN}{550} \text{ in engine}$$

$$BHP = \frac{2\pi QN}{550} \text{ at engine coupling}$$

$$SHP = \frac{d^4 G\theta N}{613033L_s} \text{ at shaft before prop}$$

DHP or PHP = at prop (takes into account stern tube losses)

$$THP = \frac{T\ Va}{550} \text{ powered by props}$$

$$EHP = \frac{RV}{550} \text{ power needed to drive ship}$$

$$\text{P.E. - Propulsive Eff.} = \frac{EHP}{IHP} \text{ (for diesels)}$$

$$= \frac{EHP}{SHP} \text{ (for turbines)}$$

Reference page 372 PNA

Propulsive Coefficient (or Quasi-Propulsive Coefficient) $= \frac{EHP}{PHP} = \frac{EHP}{THP} \times \frac{THP}{PHP}$

Table 2

POLAR STAR open water performance (Test 6A)

| SP (KTS) | SP (FPS) | EHP | RESIST (LBS) | SHP | THRUST (LBS) (At shaft) | PC | TORQUE (FT LBS) (Total) |
|---|---|---|---|---|---|---|---|
| 4 | 6.76 | | | | | | |
| 6 | 10.14 | | | | | | |
| 8 | 13.52 | 600 | 24,408 | 1000 | 40,608 | .60 | 29,980 |
| 10 | 16.90 | 1150 | 37,426 | 1900 | 62,376 | .60 | 56,962 |
| 12 | 20.28 | 2000 | 54,241 | 3400 | 90,401 | .60 | 101,932 |
| 14 | 23.66 | 3375 | 78,455 | 5600 | 130,759 | .60 | 167,888 |
| 16 | 27.04 | 5200 | 105,769 | 8600 | 176,282 | .60 | 257,828 |
| 18 | 30.42 | 9300 | 169,050 | 15600 | 281,744 | .60 | 467,688 |
| 20 | 33.80 | 15150 | 246,524 | 25000 | 410,872 | .59 | 749,500 |

POLAR STAR
OPEN WATER
RESIST

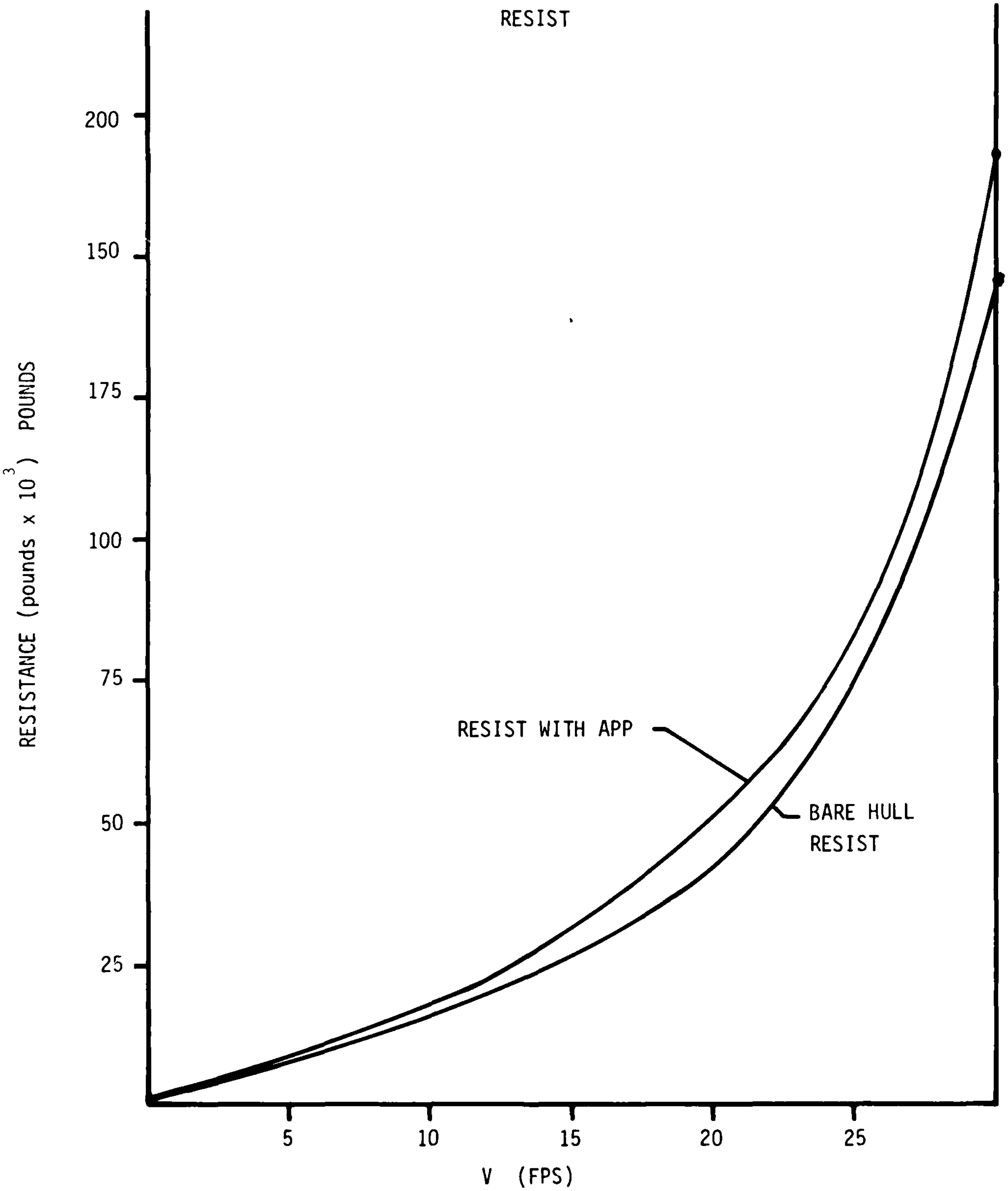



FIGURE 1 VELOCITY (FEET PER SECOND)

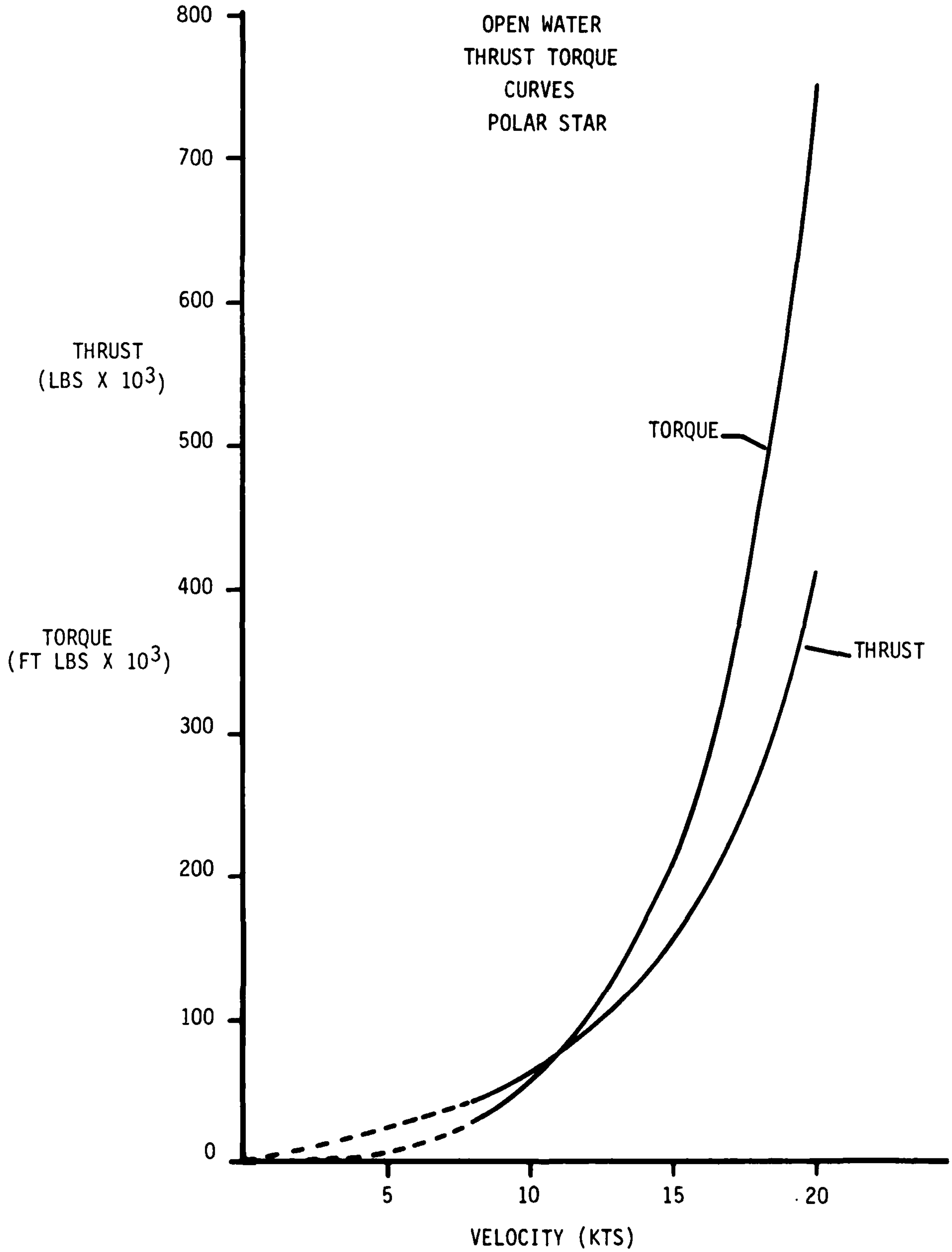

OPEN WATER
THRUST TORQUE
CURVES
POLAR STAR
800
700
600
500
400
300
200
100
0
THRUST
(LBS X 10³)
TORQUE
(FT LBS X 10³)
TORQUE
THRUST
5
10
15
20
VELOCITY (KTS)

Figure 2.

$$= dh \times e_p \times e_{rr}$$

$$\text{Propulsive Efficiency} = \frac{EHP}{PHP} \times \frac{PHP}{SHP}$$

$$= eh \times e_p \times e_{rr} \times e_t$$

$e_t$ ~ 98% mach. aft (rough approximation)

~ 97% mach. midships (rough approximation)

SHP should be measured as close to stern tubes as possible.

V-Va = wake speed
$\omega$ = wake <u>fraction</u> = $\frac{V-Va}{V}$

$Va = v(1-\omega)$

$1+\omega$ is wake <u>factor</u>

$R_t = (1 - t)T$ total resistance or available thrust

$t = \frac{T-R_t}{T} = 1 - \frac{R_T}{T}$ thrust deduction <u>fraction</u>

$(1-t)$ = thrust deduction <u>factor</u>

$$\frac{EHP}{THP} = \frac{R_T V}{T V_A} = \frac{1-t}{1-\omega} = e_h = \text{hull eff.}$$

i.e. want t small $\quad \omega$ - large

$e_p = \frac{T\ V_A}{2\pi N Q_o}$ open water prop eff.

$e_b = \frac{T\ V_A}{2\pi N Q}$ eff. of prop behind ship

$e_r = \frac{e_b}{e_o} = \frac{Q_o}{Q}$ rel. rotative eff.

$.95 < e_r < 1.1$ (rough approximation)

$$PC \text{ or } QPC = \frac{EHP}{PHP} = \frac{R_T V}{\frac{T\ V_A}{e_b}} = \frac{R_T V}{T\ V_A} e_b$$

$$= \frac{1-t}{1-\omega} e_r\ e_o$$

To go from shaft thrust to ship resistance we need

- hull efficient, i.e., $\frac{1-t}{1-\omega}$ i.e., need t and $\omega$
- need $e_p$, i.e., open water prop eff.
- need $e_r$, i.e., relative rotative eff.
- need $e_t$, i.e., transmission eff.

C. Expected values of thrust

The total thrust that can be expected at the shafts is proportional to the total resistance encountered by the ship. If we assume the propulsion coefficient presented in report P-223-H-09 is correct then the expected total thrust is presented in the enclosed table.

It should be emphasized that the thrust figure is the total and the thrust on each shaft will depend on the power distribution set by the operator, i.e., 1/3, 1/3, 1/3 or 1/2, 0, 1/2, etc.

Example calculation

$$\text{Thrust (at shaft)} = \frac{\text{RESISTANCE}}{\text{P.C.}}$$

$$\text{RESISTANCE} = \frac{\text{EHPX550}}{V}$$

$$R \text{ (16 Kts)} = \frac{5200X550}{27.04} = 105{,}769 \text{ lbs.}$$

$$\underset{\text{(Total)}}{\text{Thrust}} = \frac{105769}{.6} = 176282 \text{ lbs.}$$

D. Expected values of shaft torque

If angle of twist is measured:

$$SHP = \frac{(d_s)^4 G\ \theta\ N}{613033\ L_s}$$

G-shear modules can be taken as 11,900,000 PSI for steel shafts

N is revolutions per second

$L_s$ length over which angle $\theta$ is measured in inches

$d_s$ shaft diameter in inches

$\theta$ angle of twist in degrees over $L_s$

For torque (foot pounds)

$$SHP = \frac{2\pi\theta N}{550}$$

Q in ft lbs

N in RPS

$$RPS = \frac{RPM}{60}$$

NOTE: The same cautions exist for torque as for thrust, i.e., the power distribution and RPM must be known.

E. Example of torque calculation

$$Q = \frac{SHP\ 550}{2\pi N} = \frac{SHP\ 87.535}{N}$$

Assuming RPM of 175, i.e., 2.92 RPS and calculating total torque

$$Q = \frac{SHP\ 87.535}{2.92} = 29.98\ SHP$$

At 8 KTS open water

$$Q = 1000\ (29.98) = 29977.74 \approx 2978\ ft.\ lbs.$$

F. Propeller performance

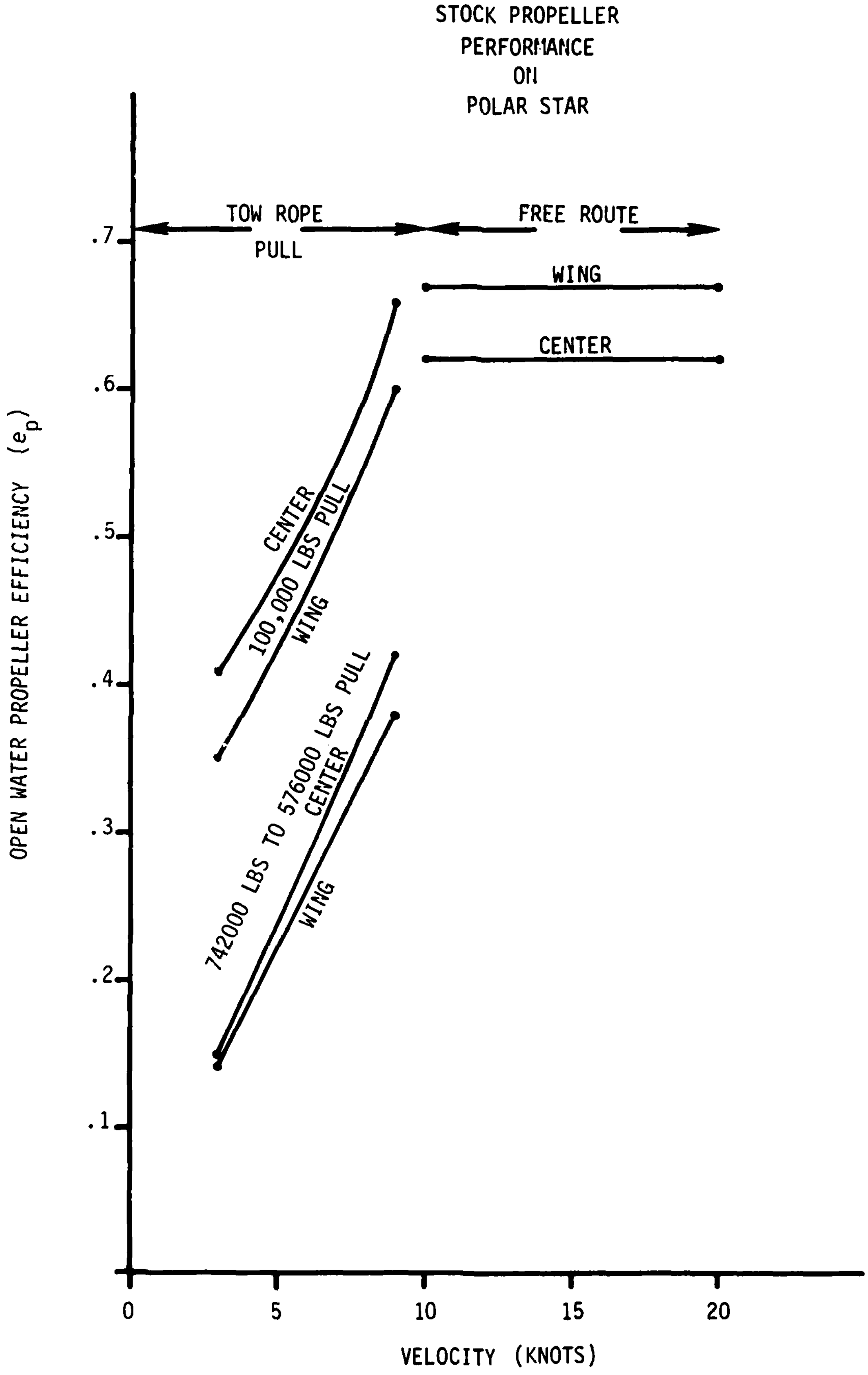
Currently no detailed (i.e., computer printout) information is available for the controllable-pitch propellers on the POLAR STAR. The enclosed tables and graph will give some indication of the degradation of propeller performance with decreasing speed in the tow rope pull condition. One must be careful in approximating the P.C. in these conditions, particularly in ice. Not only will t and w change with speed but they also will be effected by ice flow in a detrimental manner. The extent of the effect is difficult to estimate due to the lack of any model or full scale data. (See Fig. 3 and Tables 3-7).

## IV. PREDICTED ICEBREAKING PERFORMANCE CHARACTERISTICS OF THE POLAR STAR BY CDR G. P. VANCE

A. Abstract

The curves of ice resistance versus velocity for the POLAR STAR have been derived utilizing the basic program of Dr. V.R. Milano (Resistance to Ship Motion in Sheet Ice). Caution should be used when evaluating changes in resistance when there has been a dramatic change in any environmental parameter. The user should read "Variation of Ship/Ice Parameters on Ship Resistance to Continuous Motion in Ice" by V.R. Milano, (April 1975), SNAME Eastern Canadian Section paper, before using the program. The program has been modified to run on the U.S. Naval Underwater Systems Center UNIVAC 1108 computer and is on file there. The program can be called from the CG R&DC terminal with output at the CG R&DC terminal (very slow) and/or output at NUSC.

The program plots resistance versus velocity curves and thrust versus velocity curves (Fig. 4) for ice thickness from 1 to 9 feet and ship speeds from 0 to 24 feet per second. The environmental constants, with the exception of flexural ice strength, compressive ice strength, the coefficient of friction and the ice specific gravity are in the main program and are set for sea ice. The program will ask for the values of flexural ice strength ($\sigma_f$), in pounds per square foot (PSF), compressive ice strength ($\sigma_c$) in PSF, the coefficient of friction ($\mu$) and specific gravity of sea ice. Exmamples of typical runs are contained in Table 8.



STOCK PROPELLER
PERFORMANCE
ON
POLAR STAR
TOW ROPE
PULL
FREE ROUTE
WING
CENTER
CENTER
100,000 LBS PULL
WING
742000 LBS TO 576000 LBS PULL
CENTER
WING
OPEN WATER PROPELLER EFFICIENCY ($e_p$)
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
VELOCITY (KNOTS)


Figure 3

Table 3

The Test Program for the United States Coast Guard Proposed Icebreaker Design (M-14-3)

| Test Number | Test Type | Draft | Figure Number | Remarks |
|---|---|---|---|---|
| 1 | LOF | 28' | 5 | Bossing Orientation |
| 2 | EHP | 28' | 6 , 7 | Bare Hull |
| 3 | EHP | 31' | 10, 19 | Free-Route |
| 4 | SHP | 31' | 10 | Free-Route, Equal SHP/Shaft |
| 5 | EHP | 28' | 11, 12, 20 | Free-Route |
| 6 | SHP | 28' | 11, 12 | Free-Route, Equal SHP/Shaft |
| 7 | TRP-3 | 28' | 13 | Equal SHP to All Shafts |
| 8 | TRP-3 | 28' | 14 | No SHP to Center Shaft |
| 9 | TRP-3 | 28' | 15 | No SHP to Wing Shafts |
| 10 | TRP-6 | 28' | 13 | Equal SHP to All Shafts |
| 11 | TRP-6 | 28' | 14 | No SHP to Center Shaft |
| 12 | TRP-6 | 28' | 15 | No SHP to Wing Shafts |
| 13 | TRP-9 | 28' | 13 | Equal SHP to All Shafts |
| 14 | TRP-9 | 28' | 14 | No SHP to Center Shaft |
| 15 | TRP-9 | 28' | 15 | No SHP to Wing Shafts |
| 16 | BP | 28' | 13 | Ahead, Equal SHP to All Shafts |
| 17 | BP | 28' | 14 | Ahead, No SHP to Center Shaft |
| 18 | BP | 28' | 15 | Ahead, No SHP to Wing Shafts |
| 19 | BPA | 28' | 16 | Astern, Equal SHP to All Shafts |
| 20 | BPA | 28' | 17 | Astern, No SHP to Center Shaft |
| 21 | BPA | 28' | 18 | Astern, No SHP to Wing Shafts |
| 22 | CWC | 28'/31' | 19-37 | Flow Observations of Tests 3 through 21 |

Table 4

A brief description of the stock propellers used in the Testing Program for Simulating Ahead Modes of Operation for the United States Coast Guard Proposed Icebreaker Design (M-14-3)

| Propeller Number | Shaft | Shaft Direction of Rotation | Pitch / Diameter |
|---|---|---|---|
| 4305 | Starboard Wing | Outboard Right Hand | 0.80 |
| 4306 | Port Wing | Outboard Left Hand | 0.80 |
| 4307 | Center | Right Hand | 0.75 |
| 4454 | Starboard Wing | Outboard Right Hand | 1.00 |
| 4455 | Port Wing | Outboard Left Hand | 1.00 |
| 4456 | Center | Right Hand | 1.00 |

## Table 5

### Predicted Free-Route Propulsion Coefficients

(Test 4) Draft 31 feet (Zero Trim) Displacement = 12,650 Tons
Propellers 4305, 4306, 4307

| Vs Kts | EHP/SHP | t | $w_T$ C | $w_T$ W | $w_Q$ C | $w_Q$ W | $J_T$ C | $J_T$ W | $e_p$ C | $e_p$ W | Thrust (lbs) C | Thrust (lbs) W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | .60 | .15 | .17 | .08 | .17 | .11 | .66 | .72 | .62 | .67 | 48,300 | 83,300 |
| 17 | .60 | .15 | .17 | .08 | .17 | .10 | .65 | .71 | .62 | .67 | 59,200 | 102,000 |
| 18 | .59 | .16 | .17 | .07 | .17 | .09 | .64 | .70 | .62 | .67 | 76,800 | 132,600 |
| 19 | .58 | .17 | .17 | .05 | .17 | .08 | .62 | .69 | .62 | .67 | 97,900 | 169,000 |

(Test 6) Draft 28 feet (Zero Trim) Displacement = 10,870 Ton
Propellers 4454,4455,4456

| Vs Kts | EHP/SHP | t | $w_T$ C | $w_T$ W | $w_Q$ C | $w_Q$ W | $J_T$ C | $J_T$ W | $e_p$ C | $e_p$ W | Thrust (lbs) C | Thrust (lbs) W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | .65 | .14 | .17 | .06 | .18 | .08 | .83 | .89 | .73 | .70 | 16,200 | 27,600 |
| 12 | .65 | .14 | .17 | .06 | .18 | .08 | .83 | .89 | .73 | .70 | 24,000 | 40,800 |
| 14 | .65 | .14 | .17 | .06 | .18 | .08 | .83 | .89 | .73 | .70 | 33,800 | 57,400 |
| 15 | .65 | .14 | .17 | .06 | .18 | .08 | .83 | .89 | .73 | .70 | 38,900 | 66,400 |
| 16 | .65 | .15 | .17 | .06 | .19 | .08 | .83 | .89 | .73 | .70 | 45,600 | 78,100 |
| 17 | .64 | .15 | .17 | .06 | .19 | .08 | .82 | .87 | .73 | .70 | 56,300 | 97,000 |
| 18 | .63 | .16 | .17 | .06 | .19 | .08 | .79 | .85 | .72 | .70 | 73,400 | 126,900 |
| 19 | .61 | .17 | .17 | .05 | .19 | .08 | .76 | .83 | .71 | .69 | 92,200 | 159,100 |

(Test 6A) Draft 28 feet (Zero Trim) Displacement = 10,870 Tons
Propellers 4305, 4306, 4307

| Vs Kts | EHP/SHP | t | $w_T$ C | $w_T$ W | $w_Q$ C | $w_Q$ W | $J_T$ C | $J_T$ W | $e_p$ C | $e_p$ W | Thrust (lbs) C | Thrust (lbs) W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | .60 | .15 | .17 | .08 | .16 | .10 | .67 | .74 | .62 | .67 | 16,200 | 28,000 |
| 12 | .60 | .15 | .17 | .08 | .16 | .10 | .67 | .74 | .62 | .67 | 24,000 | 41,400 |
| 14 | .60 | .15 | .17 | .08 | .16 | .10 | .67 | .74 | .62 | .67 | 33,800 | 58,200 |
| 15 | .60 | .15 | .17 | .08 | .17 | .10 | .67 | .74 | .62 | .67 | 38,900 | 67,000 |
| 16 | .60 | .15 | .17 | .08 | .17 | .10 | .67 | .73 | .62 | .67 | 45,600 | 78.500 |
| 17 | .60 | .15 | .17 | .08 | .18 | .10 | .66 | .72 | .62 | .67 | 56,300 | 97,000 |
| 18 | .59 | .16 | .17 | .07 | .18 | .09 | .64 | .71 | .62 | .67 | 73,400 | 126,900 |
| 19 | .58 | .17 | .17 | .05 | .18 | .07 | .62 | .70 | .62 | .67 | 92,200 | 159,100 |

## Table 6

### Predicted Tow-Rope Pull Propulsion Coefficients

Draft = 28 feet (Zero Trim) Displacement = 10,870 Tons

Equal Power Ahead to all Shafts - Vs = 3 Knots - Test 7

| TRP (lbs) | Thrust C | (lbs) W | R/T | $W_T$ | | $W_Q$ | | $J_T$ | | $e_p$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | C | W | C | W | C | W | C | W |
| 100,000 | 41,100 | 69,900 | .93 | .30 | -.10 | .15 | .02 | .21 | .33 | .41 | .35 |
| 200,000 | 78,200 | 140,300 | .93 | .23 | -.18 | .09 | .00 | .17 | .26 | .30 | .27 |
| 300,000 | 108,300 | 217,600 | .93 | .18 | -.26 | .05 | -.02 | .15 | .24 | .25 | .23 |
| 400,000 | 152,700 | 280,800 | .93 | .14 | -.30 | .04 | -.02 | 14 | .22 | .22 | .20 |
| 500,000 | 189,500 | 351,600 | .93 | .12 | -.32 | .04 | .00 | .13 | .20 | .20 | .18 |
| 600,000 | 226,900 | 421,700 | .93 | .10 | -.33 | .04 | .04 | .12 | .18 | .18 | .17 |
| 700,000 | 264,000 | 492,100 | .93 | .06 | -.33 | .02 | .09 | .12 | .17 | .17 | .16 |
| 800,000 | 313,100 | 550,600 | .93 | .03 | -.33 | .02 | .14 | .12 | .16 | .16 | .15 |
| 876,000 | 329,100 | 616,400 | .93 | .01 | -.33 | .01 | .18 | .11 | .15 | .15 | .14 |

Equal Power Ahead to All Shafts - Vs = 6 Knots -Test 10

| TRP (lbs) | Thrust C | (lbs) W | R/T | $W_T$ | | $W_Q$ | | $J_T$ | | $e_p$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | C | W | C | W | C | W | C | W |
| 100,000 | 45,000 | 79,800 | .91 | .24 | -.09 | .24 | .07 | .38 | .45 | .51 | .47 |
| 200,000 | 84,400 | 150,100 | .91 | .26 | -.04 | .24 | .07 | .29 | .36 | .49 | .44 |
| 300,000 | 123,500 | 220,600 | .91 | .29 | -.05 | .24 | .07 | .24 | .31 | .44 | .39 |
| 400,000 | 162,500 | 291,300 | .91 | .30 | -.09 | .24 | .06 | .21 | .28 | .39 | .35 |
| 500,000 | 200,900 | 362,500 | .91 | .30 | -.11 | .24 | .06 | .19 | .26 | .36 | .32 |
| 600,000 | 239,300 | 433,800 | .91 | .29 | -.12 | .24 | .07 | .18 | .24 | .34 | .30 |
| 700,000 | 277,400 | 505,300 | .91 | .27 | -.12 | .24 | .08 | .17 | .22 | .32 | .28 |
| 800,000 | 315,600 | 576,800 | .91 | .26 | -.12 | .24 | .09 | .17 | .21 | .30 | .27 |
| 810,000 | 319,500 | 583,900 | .91 | .26 | -.12 | .24 | .09 | .16 | .20 | .29 | .27 |

## Table 6 (Continued)

Equal Power Ahead to all Shafts - Vs = 9 Knots - Test 13

| TRP (lbs) | Thrust (lbs) | | R/T | $W_T$ | | $W_Q$ | | $J_T$ | | $e_p$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | W | | C | W | C | W | C | W | C | W |
| 100,000 | 54,600 | 89,800 | .90 | .24 | .03 | .19 | .09 | .46 | .58 | .66 | .60 |
| 200,000 | 93,500 | 162,100 | .90 | .25 | .04 | .20 | .09 | .38 | .49 | .62 | .56 |
| 300,000 | 132,300 | 234,400 | .90 | .25 | .02 | .21 | .09 | .33 | .44 | .56 | .51 |
| 400,000 | 170,900 | 306,800 | .90 | .26 | .00 | .24 | .09 | .30 | .40 | .51 | .47 |
| 500,000 | 209,500 | 379,400 | .90 | .27 | .01 | .25 | .10 | .28 | .38 | .48 | .43 |
| 600,000 | 248,100 | 452,000 | .90 | .27 | .02 | .25 | .10 | .26 | .36 | .45 | .41 |
| 700,000 | 286,600 | 524,500 | .90 | .28 | .03 | .25 | .10 | .24 | .34 | .43 | .39 |
| 742,000 | 304,700 | 553,200 | .90 | .28 | .03 | .25 | .10 | .23 | .33 | .42 | .38 |

Equal Power Ahead to All Shafts - Vs = 0 Knots - Test 16

| TRP (lbs) | Thrust (lbs) | | R/T | $W_T$ | | $W_Q$ | | $J_T$ | | $e_p$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | W | | C | W | C | W | C | W | C | W |
| 100,000 | 36,800 | 67,100 | .96 | --- | | --- | | --- | | -- | |
| 200,000 | 72,900 | 133,700 | .96 | --- | | --- | | --- | | --- | |
| 300,000 | 108,300 | 202,200 | .96 | --- | | --- | | --- | | --- | |
| 400,000 | 142,400 | 274,300 | .96 | --- | | --- | | --- | | --- | |
| 500,000 | 179,700 | 340,300 | .96 | --- | | --- | | --- | | --- | |
| 600,000 | 217,900 | 409,100 | .96 | --- | | --- | | --- | | --- | |
| 700,000 | 255,600 | 475,300 | .96 | --- | | --- | | --- | | --- | |
| 800,000 | 292,600 | 547,400 | .96 | --- | | --- | | --- | | --- | |
| 900,000 | 329,500 | 618,000 | .96 | --- | | --- | | --- | | --- | |
| 926,000 | 338,600 | 635,100 | .96 | --- | | --- | | --- | | --- | |

Table 6 (Continued)

Equal Power Ahead to Wing Shafts Only - Vs = 3 Knots - Test 8

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 100,000 | 115,200 | .93 | -.09 | .05 | .27 | .35 |
| 200,000 | 223,400 | .93 | -.05 | .12 | .20 | .26 |
| 300.000 | 331,300 | .93 | -.05 | .18 | .16 | .21 |
| 400,000 | 439,500 | .93 | -.07 | .20 | .15 | .18 |
| 500,000 | 543,700 | .93 | -.07 | .26 | .13 | .17 |
| 577,500 | 631,400 | .93 | -.08 | .32 | .13 | .16 |

Equal SHP to Wing Shafts Only - Vs = 6 Knots - Test 11

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 100,000 | 130,000 | .93 | -.01 | .07 | .43 | .52 |
| 200,000 | 237,400 | .93 | -.03 | .10 | .34 | .42 |
| 300,000 | 344,100 | .93 | -.04 | .11 | .30 | .37 |
| 400,000 | 451,500 | .93 | -.06 | .12 | .27 | .34 |
| 500,000 | 558,200 | .93 | -.08 | .14 | .25 | .32 |
| 529,000 | 589,300 | .93 | -.09 | .16 | .24 | .31 |

Equal Power Ahead to Wing Shafts Only - Vs = 9 Knots Test 14

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 100,000 | 151,100 | .93 | .03 | .10 | .50 | .58 |
| 200,000 | 259,700 | .93 | .02 | .10 | .42 | .51 |
| 300,000 | 367,500 | .93 | .00 | .11 | .38 | .46 |
| 400,000 | 476,000 | .93 | -.02 | .12 | .35 | .43 |
| 468,800 | 495,800 | .93 | -.02 | .12 | .34 | .43 |

Table 6 (Continued)

Equal Power Ahead to Wing Shafts Only - Vs = 0 Knots - Test 17

| TRP (lbs) | Thrust 9lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 100,000 | 103,100 | .97 | --- | --- | --- | --- |
| 200,000 | 206,200 | .97 | --- | --- | --- | --- |
| 300,000 | 309,300 | .97 | --- | --- | --- | --- |
| 400,000 | 412,400 | .97 | --- | --- | --- | --- |
| 500,000 | 515,500 | .97 | --- | --- | --- | --- |
| 600,000 | 618,600 | .97 | --- | --- | --- | --- |
| 620,000 | 639,200 | .97 | --- | --- | --- | --- |

Ahead Power to Center Shaft Only - Vs = 3 Knots - Test 9

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 50,000 | 66,600 | .92 | .25 | .22 | .18 | .22 |
| 100,000 | 121,300 | .92 | .25 | .22 | .14 | .18 |
| 150,000 | 175,900 | .92 | .24 | .21 | .12 | .16 |
| 200,000 | 229,300 | .92 | .24 | .20 | .11 | .14 |
| 250,000 | 281,800 | .93 | .23 | .18 | .10 | .13 |
| 300,000 | 334,200 | .93 | .22 | .17 | .10 | .12 |
| 301,000 | 335,400 | .93 | .22 | .17 | .10 | .12 |

Ahead Power to Center Shaft Only - Vs = 6 Knots - Test 12

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 50,000 | 87,200 | .91 | .26 | .16 | .28 | .36 |
| 100,000 | 142,400 | .91 | .27 | .17 | .23 | .29 |
| 150,000 | 197,300 | .91 | .27 | .18 | .20 | .26 |
| 200,000 | 250,700 | .91 | .27 | .19 | .18 | .24 |
| 250,000 | 303,800 | .92 | .27 | .19 | .17 | .22 |
| 267,000 | 322,300 | .92 | .27 | .19 | .16 | .21 |

Table 6 (Continued)

Ahead Power to Center Shaft Only - Vs = 9 Knots - Test 15

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 50,000 | 128,600 | .79 | .14 | .08 | .39 | .48 |
| 100,000 | 181,900 | .83 | .13 | .07 | .34 | .42 |
| 150,000 | 236,700 | .85 | .13 | .06 | .31 | .38 |
| 200,000 | 290,800 | .86 | .13 | .04 | .29 | .36 |
| 213,000 | 305,200 | .86 | .13 | .04 | .28 | .35 |

Ahead Power to Center Shaft Only - Vs = 0 Knots - Test 18

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 50,000 | 51,500 | .97 | --- | --- | --- | --- |
| 100,000 | 103,100 | .97 | --- | --- | --- | --- |
| 150,000 | 154,600 | .97 | --- | --- | --- | --- |
| 200,000 | 206,200 | .97 | --- | --- | --- | --- |
| 250,000 | 257,700 | .97 | --- | --- | --- | --- |
| 300,000 | 309,300 | .97 | --- | --- | --- | --- |
| 337,000 | 347,400 | .97 | --- | --- | --- | --- |

Equal Power Astern to All Shafts - Vs =0 Knots - Test 19

| TRP (lbs) | Thrust C | (lbs) W | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|---|
| 100,000 | 38,100 | 70,100 | .93 | --- | --- | --- | --- |
| 200,000 | 78,800 | 146,100 | .89 | --- | --- | --- | --- |
| 300,000 | 119,900 | 226,400 | .87 | --- | --- | --- | --- |
| 400,000 | 159,600 | 306,300 | .86 | --- | --- | --- | --- |
| 500,000 | 200,000 | 381,800 | .86 | --- | --- | --- | --- |
| 600,000 | 238,000 | 459,700 | .86 | --- | --- | --- | --- |
| 700,000 | 276,300 | 536,400 | .86 | --- | --- | --- | --- |
| 800,000 | 315,300 | 613,600 | .86 | --- | --- | --- | --- |
| 892,000 | 352,700 | 683,500 | .87 | --- | --- | --- | --- |

Table 6 (Continued)

Equal Power Astern to Wing Shafts Only - Vs = 0 Knots - Test 20

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 100,000 | 119,000 | .84 | ---- | ---- | ---- | ---- |
| 200,000 | 240,600 | .83 | --- | --- | --- | --- |
| 300,000 | 362,500 | .83 | --- | --- | --- | --- |
| 400,000 | 484,400 | .83 | --- | --- | --- | --- |
| 500,000 | 606,000 | .83 | --- | --- | --- | --- |
| 561,000 | 686,000 | .83 | --- | --- | --- | --- |

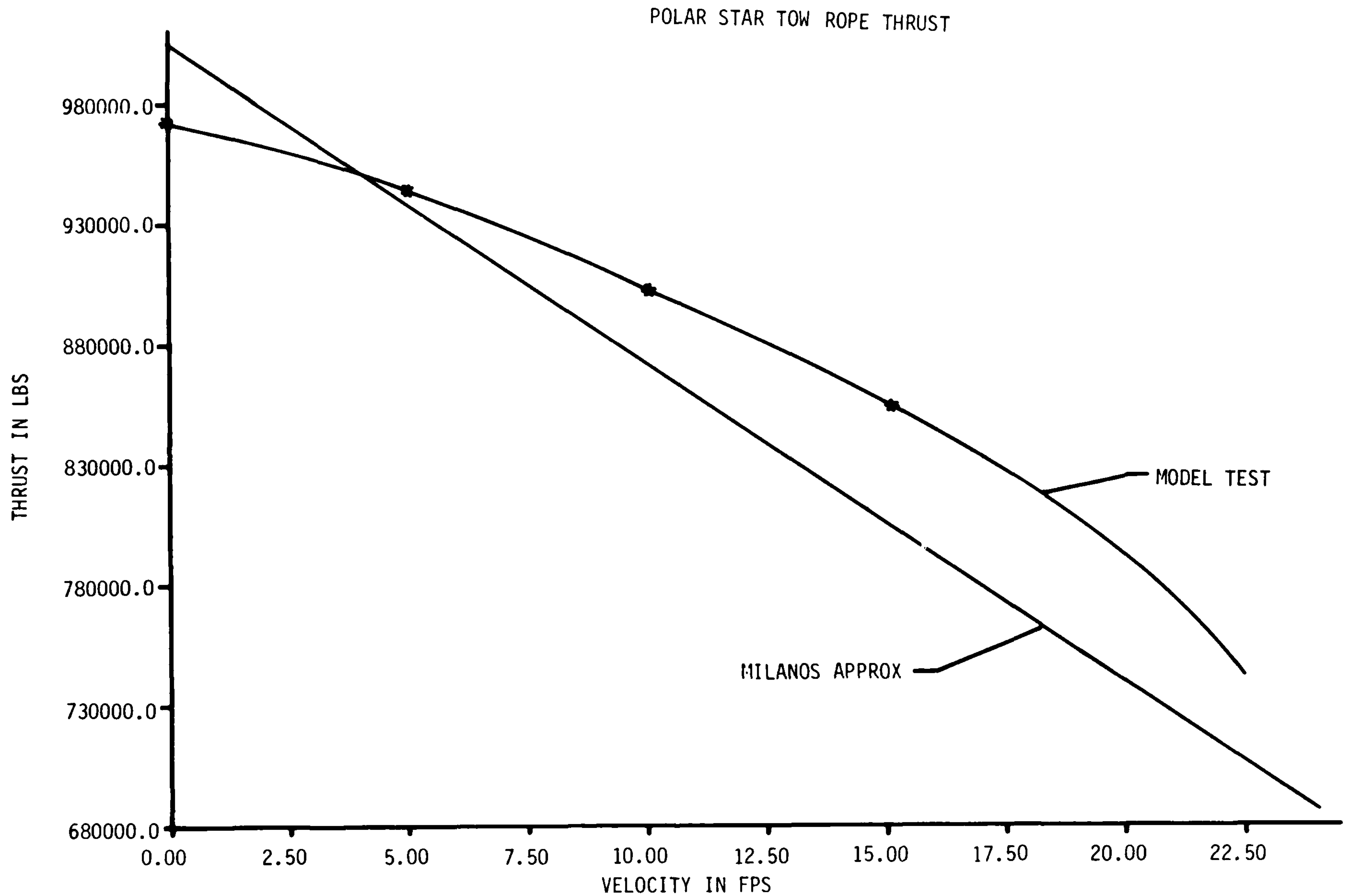
Astern Power to Center Shaft Only - Vs = 0 Knots - Test 21

| TRP (lbs) | Thrust (lbs) | R/T | $W_T$ | $W_Q$ | $J_T$ | $e_p$ |
|---|---|---|---|---|---|---|
| 50,000 | 61,600 | .81 | --- | --- | --- | --- |
| 100,000 | 124,800 | .80 | --- | --- | --- | --- |
| 150,000 | 187,100 | .80 | --- | --- | --- | --- |
| 200,000 | 247,300 | .81 | --- | --- | --- | --- |
| 250,000 | 307,400 | .81 | --- | --- | --- | --- |
| 290,000 | 355,700 | .81 | --- | --- | --- | --- |

Table 7

Summary of Predicted Towing Performance for the M-14-3 Design Icebreaker
Shaft Horsepower = 20,000 SHP/SHAFT

| VS KTS | RPM C | RPM W | TRP (lbs) | Thrust (lbs) C | Thrust (lbs) W | Total SHP |
|---|---|---|---|---|---|---|
| Maximum Power to All Shafts | | | | | | |
| 0 Astern | 164.5 | 157.8 | 892,000 | 352,700 | 683,500 | 60,000 |
| 0 Ahead | 165.6 | 158.6 | 926,000 | 338,600 | 635,100 | 60,000 |
| 3 Ahead | 167.1 | 163.7 | 876,000 | 329,100 | 616,400 | 60,000 |
| 6 Ahead | 170.0 | 168.3 | 810,000 | 319,500 | 583,900 | 60,000 |
| 9 Ahead | 176.9 | 175.8 | 742,000 | 304,700 | 553,200 | 60,000 |
| Maximum Power to Wing Shafts - No Power to Center Shaft | | | | | | |
| 0 Astern | Wind Milling | 158.9 | 561,000 | ____ | 686,200 | 40,000 |
| 0 Ahead | Wind Milling | 157.8 | 620,000 | ____ | 639,200 | 40,000 |
| 3 Ahead | Wind Milling | 162.3 | 577.500 | ____ | 631,400 | 40,000 |
| 6 Ahead | Wind Milling | 168.8 | 529,000 | ____ | 589,300 | 40,000 |
| 9 Ahead | Wind Milling | 175.2 | 468,800 | ____ | 547,400 | 40,000 |
| Maximum Power to Center Shaft - No Power to Wing Shafts | | | | | | |
| 0 Astern | 164.2 | Wind Milling | 290,000 | 355,700 | ____ | 20,000 |
| 0 Ahead | 162.7 | Wind Milling | 337,000 | 347,400 | ____ | 20,000 |
| 3 Ahead | 166.8 | Wind Milling | 301,000 | 335,400 | ____ | 20,000 |
| 6 Ahead | 171.1 | Wind Milling | 267,000 | 322,300 | ____ | 20,000 |
| 9 Ahead | 176.9 | Wind Milling | 213,000 | 305,200 | ____ | 20,000 |




THRUST VS VELOCITY

Figure 4

Table 8

Summary of runs

| Run | Ship | $\sigma_f$ (PSF) | $\sigma_c$ (PSF) | $\mu$ | SG ICE | Remarks |
|---|---|---|---|---|---|---|
| 1. | POLAR STAR | 10,000 | 100,000 | .2 | 1.03 | CG R&DC Ouput |
| 2. | POLAR STAR | 10,000 | 100,000 | .2 | | |
| 3. | POLAR STAR | 12,000 | 100,000 | .2 | | |
| 4. | POLAR STAR | 15,000 | 100,000 | .2 | | |
| 5. | POLAR STAR | 10,000 | 100,000 | .4 | | |
| 6. | POLAR STAR | 10,000 | 200,000 | .2 | | |
| 7. | POLAR STAR | 10,000 | 100,000 | .2 | | |
| 8. | POLAR STAR | 10,000 | 100,000 | .2 | | Plot RT Change<br>Plot to Milano |
| 9. | POLAR STAR | 15,000 | 100,000 | .2 | | |
| 10. | POLAR STAR | 20,000 | 100,000 | .2 | | |
| 11. | POLAR STAR | 10,000 | 100,000 | .2 | | Plot missing |
| 12. | WIND | 24,000 | 40,000 | .2 | .92 | Same as Milano<br>SG ice changed<br>$\sigma_f$ high, ODR RES |
| 13. | WIND | 10,000 | 100,000 | .2 | | |
| 14. | POLAR STAR | 10,000 | 100,000 | .2 | | |
| 15. | POLAR STAR | 20,000 | 100,000 | .2 | | |
| 16. | POLAR STAR | 12,000 | 100,000 | .2 | | |
| 17. | POLAR STAR | 15,000 | 100,000 | .2 | | |
| 18. | POLAR STAR | 10,000 | 100,000 | .1 | | |
| 19. | POLAR STAR | 15,000 | 100,000 | .3 | | Term doubt |
| 20. | POLAR STAR | 15,000 | 100,000 | .3 | | Term doubt |
| 21. | POLAR STAR | 15,000 | 50,000 | .2 | | Printout missing |
| 22. | POLAR STAR | 15,000 | 50,000 | .3 | | |
| 23. | WIND | 15,000 | 50,000 | .2 | | |
| 24. | MACKINAW | 15,000 | 50,000 | .2 | | |

Table 8 (Continued)

| Run | Ship | $\sigma_f$ (PSF) | $\sigma_c$ (PSF) | $\mu$ | SG ICE | Remarks |
|---|---|---|---|---|---|---|
| 25. | MACKINAW | 20,000 | 50,000 | .2 | .92 | |
| 26. | MACKINAW | 30,000 | 50,000 | .2 | .92 | |
| 27. | POLAR STAR | 30,000 | 50,000 | .2 | .92 | |
| 28. | POLAR STAR | 15,000 | 50,000 | .2 | .82 | CHD pro to call for SPGR ice |
| 29. | POLAR STAR | 15,000 | 50,000 | .1 | .82 | |
| 30. | POLAR STAR | 20,000 | 50,000 | .2 | .92 | |
| 31. | MACKINAW | 20,000 | 50,000 | .2 | .92 | |
| 32. | POLAR STAR | 12,000 | 50,000 | .2 | .92 | |
| 33. | POLAR STAR | 15,000 | 50,000 | .2 | .96 | |
| 34. | POLAR STAR | 15,000 | 52,500 | .2 | .92 | |
| 35. | POLAR STAR | 15,000 | 45,000 | .2 | .92 | |
| 36. | POLAR STAR | 14,300 | 50,000 | .2 | .92 | |
| 37. | POLAR STAR | 16,000 | 50,000 | .2 | .92 | |
| 38. | POLAR STAR | 18,000 | 50,000 | .2 | .92 | |
| 39. | POLAR STAR | 15,000 | 50,000 | .1 | .92 | |
| 40. | POLAR STAR | 15,000 | 50,000 | .25 | .92 | |
| 41. | POLAR STAR | 15,000 | 50,000 | .235 | .92 | |
| 42. | MACKINAW | 20,000 | 50,000 | .2 | .945 | FR water |
| 43. | POLAR STAR 30' | 15,000 | 50,000 | .2 | .945 | FR water |
| 44. | POLAR STAR 30' | 15,000 | 50,000 | .2 | .92 | Salt water |
| 45. | POLAR STAR 28' | 15,000 | 50,000 | .2 | .92 | GML=3501.1<br>G BETA 14 ST |
| 46. | POLAR STAR 30' | 15,000 | 50,000 | .2 | .92 | G DELT 14 ST |

B. Introduction

The ship data is read into the program as data file. At present the program is set up such that the data file for the ship of interest must be called for. The POLAR STAR data is contained in a data package called ICEDTA. Any ship's data can be called for by using the @ ASGA (file name) and the @ USE 15. (file name), cards. The following tables describe the program input data, with examples for the POLAR STAR (Table 9), the WINDCLASS (Table 10) and the MACKINAW (Table 11), the program constants and the program output. The wind data is contained in a file called WINDTA, the MACKINAW data is in a file called MACDTA.

Once the terminal is activated by turning it on, dialing NUSC (447-3251) and entering the CG R&DC ID U1108P, the runs are made by following the enclosed samples.

The printout of the curves of Resistance versus Velocity and Thrust versus Velocity are contained in appendix A of this report.

C. Nomenclature for ice resistance program (Input)

| | | |
|---|---|---|
| 1. | RLEN | Length between perpendiculars in feet |
| 2. | BX | Maximum beam in feet |
| 3. | DEL | Displacement in tons |
| 4. | SHP | Shaft horsepower per shaft in horsepower |
| 5. | PDIA | Propeller diameter in feet |
| 6. | X | Distance from bow to the section of maximum beam in feet |
| 7. | DELD | Distance from maximum beam to LCG IN FEET (aft is positive) |
| 8. | CBXL2 | Distance from maximum beam to amidship in feet (aft is positive) |
| 9. | DRAFT | Draft in feet |
| 10. | CX | Midship section coefficient |
| 11. | CW | Waterplane coefficient |
| 12. | GML | Longitudinal metacentric height in feet at stated draft |
| 13. | ALPHA | Angle of inclination of the bow measured from horizontal in radians |
| 14. | ALCG | Distance from LCG to LCF in feet (aft is positive) |
| 15. | NP | Number of propellers |
| 16-18 | CBI (I) | Station beam coefficient, $C_{bi}=B_i/B_x$ a 21 component array from station 0 to 20 |
| 19-21. | CXI (I) | Station area coefficient $C_{xi}=A_{xi}/A_x$ a 21 component array from station 0 to 20 |

Table 9

POLAR STAR input data (ICEDTA) 28 foot draft

```
*TERMINAL INACTIVE*
>@RUN TDSMET, X832JOESMITH,A99614STC000,60,500
DATE:  061775      TIME: 152842
>@ASG,AX ICEDTA.
READY
>@DATA,L ICEDTA.
12345678901234567890123456789012345678901234567890123456789012345678901234567890012
25:>P 1 40
352.0
78.0
10863.0
20000.0
16.0
140.g
33.3
35.2
28.0
.852
.740
350.1
.26179
1.35
         3
0.0        .242        .465        .648        .789        .890        .955
.989       1.0         .999        .990        .974        .953        .925
.883       .823        .740        .622        .459        .249        .000
0.0        .032        .150        .353        .556        .735        .856
.922       .973        .992        1.0         .968        .911        .824
.714       .636        .406        .267        .150        .032        .000
.524       .593        .716        .794        .922        1.114       1.257
1.295      1.309       1.326       1.335        1.344       1.335        1.274
.489       .471        .419        .353        .257        .175        .112
.056       0.0         0.0         0.0         0.0         0.0         0.0
1.
2.
3.
4.
5.
6.
7.
8.
9.
0.0
SCAN:4
EOF:35
0:>SCALE 1
12345678901234567890123456789012345678901234567890123456789012345678901234567890012
0:>EXIT
LINES:35 FIELDATA
>@FREE ICEDTA.
READY
>@@SKIP 60
>@FIN
```

Table 10

WINDCLASS input data (WINDTA)

```
12345678901234567890123456789012345678901233456789012345678901234567890123456789012
25:>P 1 40
250.0
63.75
5300.0
5000.
17.
125.
1.
0.
25.75
.752
.724
201.4
.523
-.220
          2
   0.0     0.225        .432        .605        .737        .840        .910
 .958        .982        .992        1.0        .993        .9770       .951
 .91        .844        .754        .630         .462         .246         0.0
   0.0         .045          .202        .386         .554         .696         .810
  .895         .947        .980        1.0         .997         .978         .929
  .854         .741        .593         .415         .250         .079        0.
   .916         .916       .960         1.082       1.169       1.239         1.265
1.274       1.274       1.274       1.274      1.274       1.274       1.274
  .526         .471       .436        .367       .285         .209         .148
  .087         .052        .026       0.        0.0         0.0         0.0
1.
2.
3.
4.
5.
6.
7.
8.
9.
0.0
SCAN:4
EOF:35
0:>SCALE 1
1234567890123456789012345678901234567890123456789012345678901234567890123456789012
0:>
```

Table 11

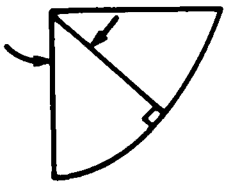
MACKINAW input data (MACDTA.)

```
12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
25:>P 1 40
280.
70.
5252.
5000.
17.
140.
1.0
00.
19.
.812
.728
321.5
.523
.1
         2
0.000        0.236       0.434       0.599        0.732       0.830       0.906
0.957        0.983       0.997       1.000        0.998       0.984       0.957
0.917        0.855       0.769       0.644        0.473       0.221       0.0
0.000        0.052       0.239       0.411        0.567       0.699       0.809
0.891        0.950       0.985       1.000        0.993       0.958       0.906
0.809        0.676       0.527       0.351        0.181       0.047       0.0
0.843        0.855       0.890       0.942        0.994       1.047       1.094
1.143        1.178       1.204       1.213        1.213       1.204        1.18
0.532        0.489       0.436       0.367        0.300       0.227       0.166
0.105        0.061       0.035       0.018        0.0         0.0          0.0
1.
2.
3.
4.
5.
6.
7.
8.
9.
0.0
SCAN:4
EOF:35
0:>SCALE 1
12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
0:>EXIT
LINES:35 FIELDATA
>
```

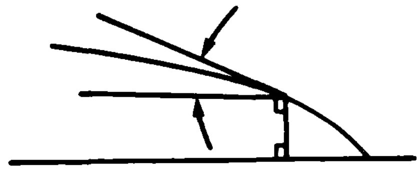
22-23. GBETA (I) Station transverse spread angle complement in radians an 11 or 15 component array station 0 to 10 or 14 taken from body plan depending on location of maximum beam

24-25. GDELT (I) Station waterline inclination in radian an 11 or 14 component array station 0 to 10 or 13 taken from half breadth plan depending on location of maximum beam

GBETA (I)



GDELT (I)



26-34. HICE Ice thickness in feet

35. Termination of loop with 0.0 ice thickness

D. Nomenclature for ice resistance program (Program constants)

1. RHOW Mass density of water in LBsec$^2$/FT$^4$ normally taken as 1.99

2. RHOI Mass density of ice in LBsec$^2$/FT$^4$ normally taken as 1.79

3. GAMW Specific weight of water normally taken as 65.0 LB/FT$^3$

4. SPGR Specific gravity of ice normally taken .92

5. SIG Tensile (flexural) strength of ice in LB/FT$^3$. In the area of 10,000 PSF for seawater ice and 20,000 PSF for fresh water ice. This value should be investigated by user.

6. SIGC Compressive strength of ice in LB/FT$^2$. This value depends on ice temperature. 50,000 can be taken as an average value.

7. FRICT Coefficient of dynamic friction. This value will vary and should be investigated by user. Range of values would be .1 to .5.

8. XNU Kinematic viscosity of water normally taken as 1.97 x $10^{-5}$ FT$^2$/sec

9. GRA Acceleration of gravity normally taken as 32.2 FT/sec$^2$

10. DELCF Hull roughness allowance normally taken as .0004 (used for open water resistance)

11. PSIO Bow wedge included angle normally taken as 1.18 radians

12. PSIC — Cusp wedge included angle normally taken as 1.85 radians

13. E — Young modulus for ice normally taken as $1 \times 10^8$ LB/FT$^2$

14. XK — Foundation (water) modulus normally taken as 64 LB/FT$^2$

15. ACCYF — An epsilon factor used in computing open water resistance normally taken as .001E-3

E. Nomenclature for ice resistance program (Output)

1. HICE — Ice thickness in feet
2. U — Ship speed in feet per second
3. E1 — Energy through ice filled channel in foot pounds
4. THURST — Total thrust available in pounds
5. TT1 — Time to break
6. E3 — Energy for climbing on ice in foot pounds
7. TT — Time in seconds
8. E4 — Energy for fracturing ice in foot pounds
9. E5 — Energy for submerging ice in foot pounds
10. E21 — Energy for local crushing in foot pounds
11. ET — Total energy in foot pounds
12. FT — Total resistance in pounds
13. XFT — Non-dimensional resistance ($R/\rho gBH^2$)
14. XFROU — Thickness froude number ($U/\sqrt{gh}$)
15. XSIG — Non-dimensional strength ($\sigma/\rho gh$)

F. POLAR STAR station beam coefficient

| STA | BEAM/2 | Bi/Bx |
|---|---|---|
| 0 | 0 | .000 |
| 1 | 9-5-2 | .242 |
| 2 | 18-1-5 | .465 |
| 3 | 25-3-1 | .648 |
| 4 | 30-9-0 | .789 |
| 5 | 34-8-2 | .890 |

| STA | BEAM/2 | Bi/Bx |
|---|---|---|
| 6 | 37-2-5 | .955 |
| 7 | 38-6-6 | .989 |
| *8 (bx) | 38-11-7 | 1.000 (38.9895) |
| 9 | 38-11-6 | .999 |
| 10 | 38-7-2 | .990 |
| 11 | 37-11-5 | .974 |
| 12 | 37-2-0 | .953 |
| 13 | 36-0-7 | .925 |
| 14 | 34-5-0 | .883 |
| 15 | 32-1-0 | .823 |
| 16 | 28-10-3 | .740 |
| 17 | 24-3-3 | .622 |
| 18 | 17-10-5 | .459 |
| 19 | 9-8-5 | .249 |
| 20 | 0 0 0 | .000 |

G. POLAR STAR station area coefficient

| STA | AREA | Ai/Ax |
|---|---|---|
| 0 | 0 | .000 |
| 1 | 60 | .032 |
| 2 | 280 | .150 |
| 3 | 660 | .353 |
| 4 | 1040 | .556 |
| 5 | 1374 | .735 |
| 6 | 1600 | .856 |
| 7 | 1725 | .922 |
| 8 | 1820 | .973 |
| 9 | 1855 | .992 |

| STA | AREA | Ai/Ax |
|---|---|---|
| 10 | 1870 | 1.000 |
| 11 | 1810 | .968 |
| 12 | 1704 | .911 |
| 13 | 1540 | .824 |
| 14 | 1336 | .714 |
| 15 | 1190 | .636 |
| 16 | 760 | .406 |
| 17 | 500 | .267 |
| 18 | 280 | .150 |
| 19 | 60 | .032 |
| 20 | 0 | .000 |

- (See Figure 5) -

H. Transverse spread angle complement [GBETA (I)]

| STA | ANGLE (DEC) | ANGLE (RAD) |
|---|---|---|
| 0 | 30.0 | .524 |
| 1 | 34.0 | .593 |
| 2 | 41.0 | .716 |
| 3 | 45.5 | .794 |
| 4 | 52.8 | .922 |
| 5 | 63.8 | 1.114 |
| 6 | 72.0 | 1.257 |
| 7 | 74.2 | 1.295 |
| 8 | 75.0 | 1.309 |
| 9 | 76.0 | 1.326 |
| 10 | 76.5 | 1.335 |
| 11 | 77.0 | 1.344 |
| 12 | 76.5 | 1.335 |
| 13 | 73.0 | 1.274 |

POLAR STAR

SECTION AREA CURVE

(28 FT. W.L.)

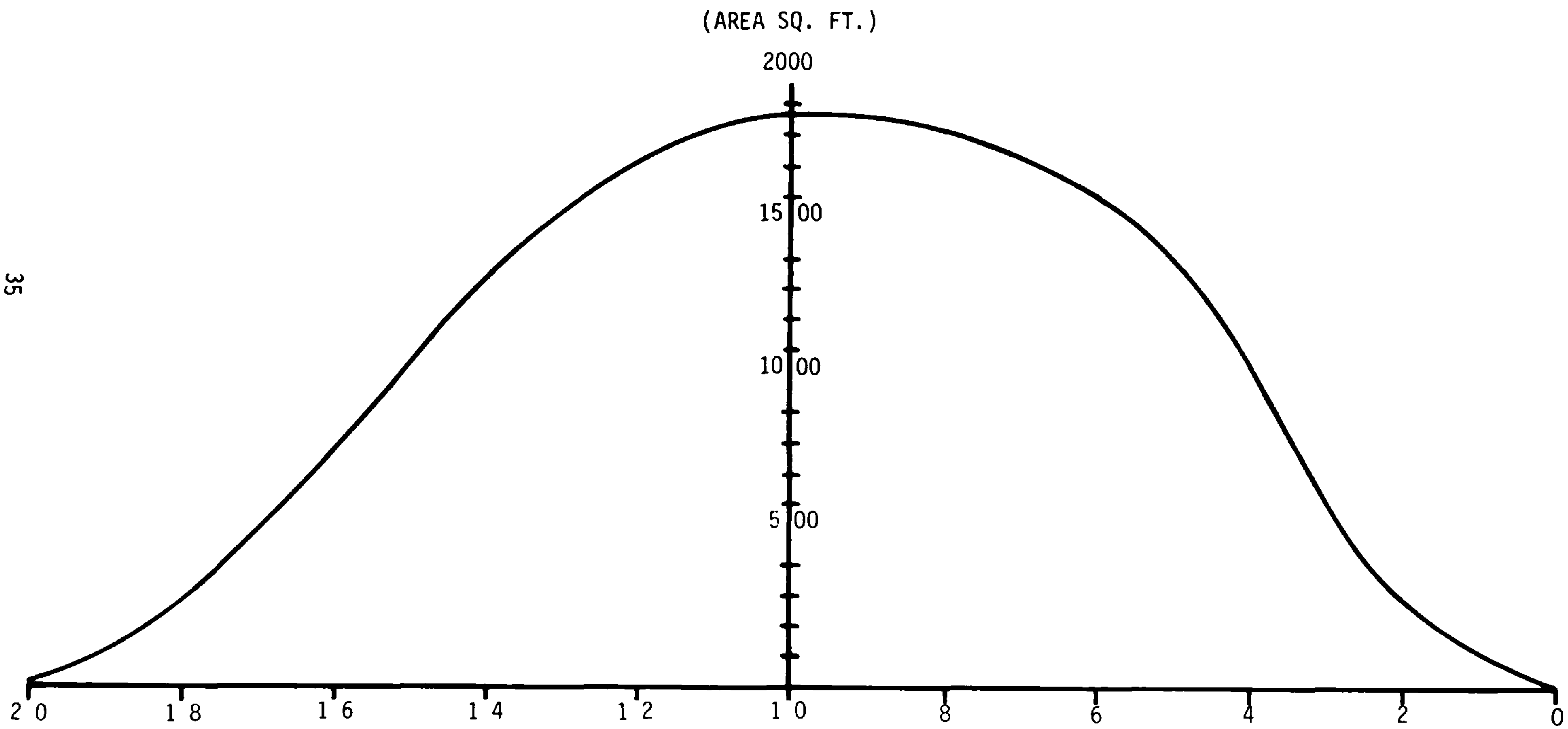



Figure 5

| STA | ANGLE (DEC) | ANGLE (RAD) |
|---|---|---|
| 14 | 71.0 | 1.239 |
| 15 | 66.8 | 1.166 |

I. Station waterline inclination [GDELT (I)]

| STA | ANGLE (DEG) | ANGLE (RADIANS) (Used) | ANGLE (RADIANS) (Act) |
|---|---|---|---|
| 0 | 28 | .489 | |
| 1 | 27 | .471 | |
| 2 | 24 | .419 | |
| 3 | 20.25 | .353 | |
| 4 | 14.70 | .257 | |
| 5 | 10.00 | .175 | |
| 6 | 6.4 | .112 | |
| 7 | 3.2 | .056 | |
| 8 | 0.0 | .000 | |
| 9 | -1.0 | .000 | -.017 |
| 10 | -2.0 | .000 | -.035 |
| 11 | -2.5 | .000 | -.044 |
| 12 | -3.5 | | -.061 |
| 13 | -5.0 | | -.087 |
| 14 | -7.0 | | -.122 |
| 15 | -10.0 | | -.175 |

J. Expected thrust values when breaking ice

The thrust experienced at the shafts when breaking ice will be directly proportioned to the resistance experienced by the vessel. The expected value of total thrust (as in open water, the distribution of power on the shafts is up to the operator) can be found by referring to the resistance curve that matches the operating conditions. All that need be done to find total thrust at the shaft is divide the total resistance by the propulsive coefficient.

Example calculation from Run #21

$\sigma_f$ = 15,000 PSF  $\sigma_c$ = 50,000 PSF  $\mu$ = .2  SG = .92

R = 340,000 lbs.

$$Tshaft = \frac{R}{PC} = \frac{340,000}{.6}$$

566,667 lbs. (total)

NOTE: The P.C. may be less than .6, which was taken from the open water tests, because of the ice interrupting the water flow about the propellers.

K. Expected torque values when breaking ice

When in the icebreaking mode, the torques experienced on the shafts will be much higher than those experienced while in open water. The torque will depend on the total resistance of the vessel as well as the speed through the ice.

In order to estimate the torque the power distribution (i.e., 1/3, 1/3, 1/3) must be specified. The total resistance is distributed accordingly (another assumption) and the resistance changed to EHP which is converted to SHP, using a P.C. of approximately .6 (another assumption, the P.C. will probably be lower because of ice interferring with water flow). The SHP can be converted to shaft torque knowing the RPM of the shaft.

This procedure does not take into account any torques that may be encountered due to interaction between the ice and the propeller itself. These torques (i.e., ice-propeller) will show up as large peaks on an oscillograph or recorder record and can be eliminated from any power calculation if desired.

L. Calculation of expected ice resistance torque

$$Q = \frac{550\ SHP}{2\pi\ N}$$

N - RPS  S - FT LBS

$$SHP = \frac{EHP}{P.C.}$$

$$P.C. = e_h\ e_p\ e_{rr}\ e_t$$

$$EHP = \frac{\text{Ice resistance x vel}}{500}$$

Ice resist = lbs (obtained from Resist Curves)

VEL - FPS

NOTE: Ice resistance must be divided in accordance with power distribution example calculation

Ice resistance = 340,000 lbs

From plots R vs V for run #21

13 FPS (7.7 KTS) 4 ft ice $\sigma_f$ = 15,000 PSF  $\mu$ = .2

$\sigma_c$ = 50,000 SG = .92 RPM = 175

$$EHP = \frac{340,000 \times 13}{550} = 8036$$

$$\frac{EPH}{3} = \frac{8036}{3} = 2678.8$$

$$SHP = \frac{EHP}{P.C.} = \frac{2678.8}{.6} = 4464.6$$

$$Q_{cs} = \frac{550\ SHP}{2\pi\ N} = \frac{550\ (4464.6)}{2\pi\ 2.92}$$

Q = 133906 ft lbs per shaft rotating at 175 RPM

M. Prediction program vertification

Although the program may be over sensitive to the various parameters entered, both ship and environment, one can obtain an appreciation of its relative merit by comparing the output for the POLAR STAR with the MACKINAW. The MACKINAW output can then be compared to full-scale data obtained in field tests. This is done for Run #21 and Run # 24 (i.e., thickness plot - see Figs. 6-7).

The comparison must be made with care since Run #21, and Run #24 made with the following parameters:

$\sigma_f$ = 15,000 PSF

$\sigma_c$ = 50,000 PSF

$\mu$ = .2

SG = .92

The program appears to predict a resistance that is 15 percent lower than full scale at speeds greater than 7 FPS (4.2 KTS). There may be several reasons for this discrepancy:

- The coefficient of friction may not have been measured correctly in the field
- The environmental or power parameters may not have been correctly determined in the field
- The program algorithms may not be correct.

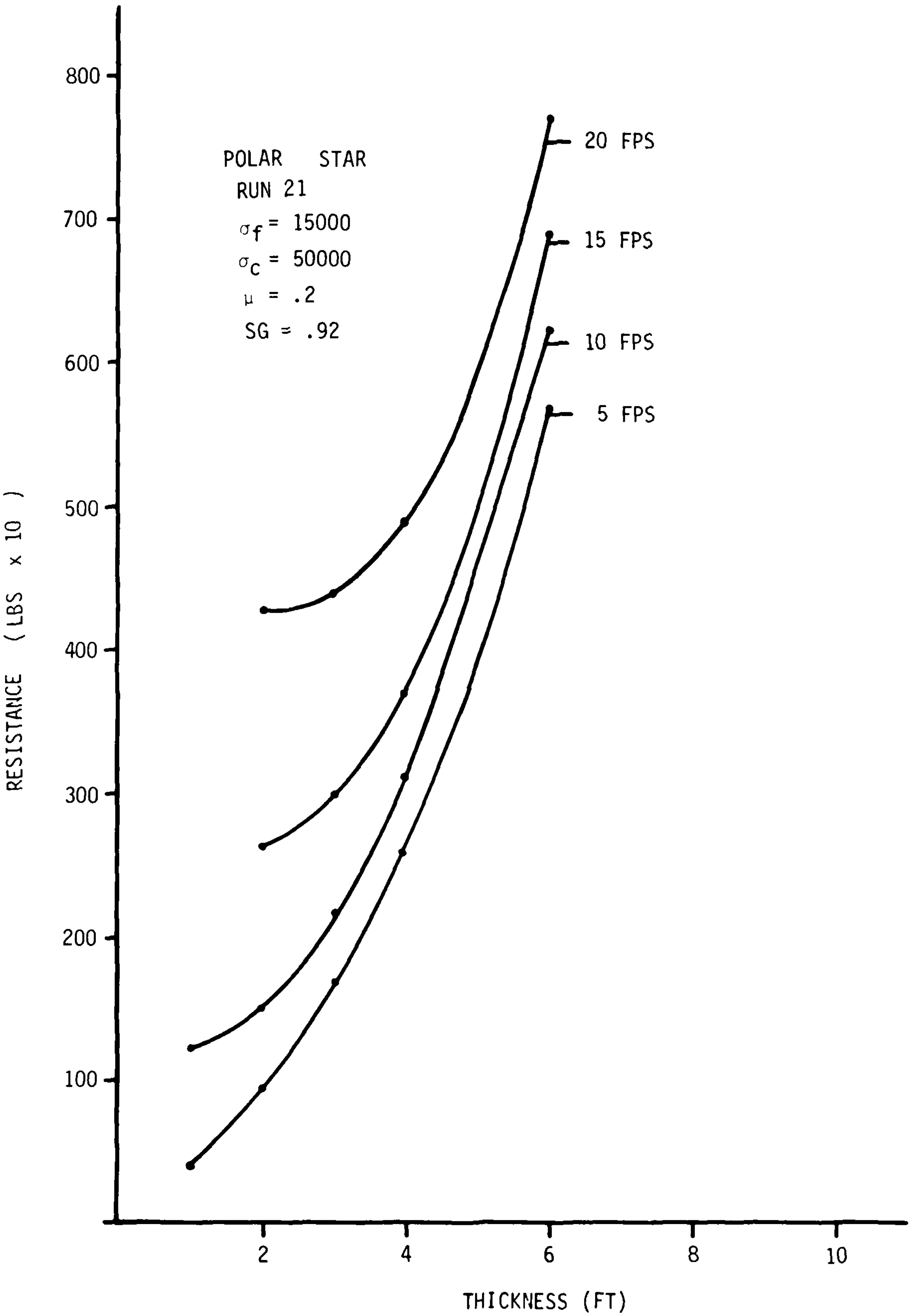
In any event, one should be aware of these shortcomings when comparing field data with the program output.

V. PREDICTION OF ERROR SOURCES FOR FULL SCALE TEST OF POLAR STAR BY G. P. VANCE

A. Abstract

An error analysis, based on Dr. Milano's resistance prediction program is made. The resulting error in predicting resistance from errors made in measuring environmental and shipboard parameters are presented.

The analysis indicates that velocity, ice thickness and the specific gravity of the ice are the most important parameters to be measured. Flexural



POLAR STAR
RUN 21
$\sigma_f$ = 15000
$\sigma_c$ = 50000
$\mu$ = .2
SG = .92
20 FPS
15 FPS
10 FPS
5 FPS
RESISTANCE (LBS x 10 )
800
700
600
500
400
300
200
100
2
4
6
8
10
THICKNESS (FT)


Figure 6.

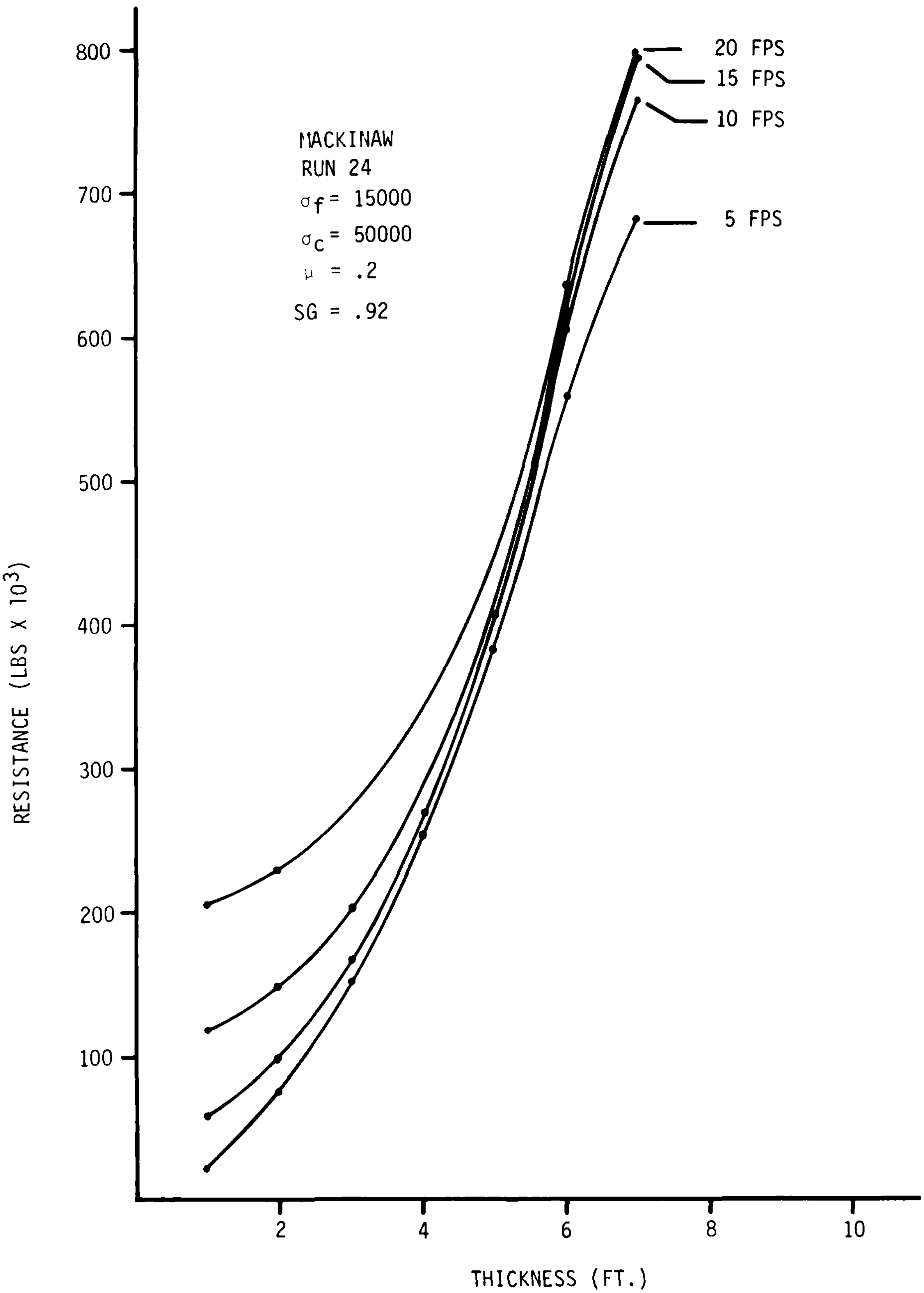

MACKINAW
RUN 24
$\sigma_f$ = 15000
$\sigma_c$ = 50000
$\mu$ = .2
SG = .92
20 FPS
15 FPS
10 FPS
5 FPS
RESISTANCE (LBS X $10^3$)
THICKNESS (FT.)
800
700
600
500
400
300
200
100
2
4
6
8
10

Figure 7

strength and friction coefficients must also be measured; however, small errors in these values do not lead to significant errors in the resistance predicted.

Any errors made in measuring propulsion parameters will lead to a corresponding error in calculating resistance.

B. Introduction

The effect of various parameters, both environmental and machinery, will have different impacts on computation of the overall resistance of the POLAR STAR in ice.

It would be a fairly simple matter to evaluate the impact of these various parameters if there was a verified algorithm that was available that could isolate each parameter; unfortunately, there is no wide spread agreement on such an algorithm. Lewis (1972), Enkvist (1972), Milano (1972) and Vance (1974) have all published information along these lines. Although there is fair agreement on some of the parameters involved, Milano's presentation depends solely on ship and environmental parameters and will be used in this study to determine their effect on the overall resistance.

In addition to the difficulty pointed out above, there is also the problem of the interaction of various parameters, i.e., the effect of ice flexural strength increases with a decrease in ship speed and ice thickness. Thus, when attempting to determine measurement precision, these various interactions must be taken into consideration.

This analysis is based on the ship operating at its design waterline of 28 feet.

C. Program Parameters

1. Milano's Algorithm

Ship Parameters - Invariant, determined from ship's plans

Environmental Parameters:

Thickness of ice
Flexural strength of ice
Compressive strength of ice
Density of ice
Density of water
Specific gravity of ice
Coefficient of dynamic friction
Specific gravity of water
Velocity

2. Vance's Algorithm

Ship Parameters - Invariant, determined from ship's plans

Environmental Parameters:

Thickness of ice
Flexural strength of ice
Density of ice
Density of water
Coefficient of dynamic friction
Velocity

D. Effect of thickness

1. Run 21

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .92

| V = 5 FPS (3 KTS) | % INC TH | % INC RES |
|---|---|---|
| $R_1$ = 40,000 lbs | | |
| | 50.0 | 56.5 |
| $R_2$ = 92,000 lbs | | |
| | 33.3 | 46.5 |
| $R_3$ = 172,000 lbs | | |
| | 25.0 | 33.3 |
| $R_4$ = 258,000 lbs | | |
| | 20.0 | 30.2 |
| $R_5$ = 370,000 lbs | | |

| V = 10 FPS (6 KTS) | | |
|---|---|---|
| $R_1$ = 125,000 | | |
| | 50.0 | 16.6 |
| $R_2$ = 150,000 | | |
| | 33.3 | 31.2 |
| $R_3$ = 218,000 | | |
| | 25.0 | 29.7 |
| $R_4$ = 310,000 | | |
| | 20.0 | 31.1 |
| $R_5$ = 450,000 | | |

| V = 5 FPS (3 KTS) | | |
|---|---|---|
| $R_{2.0}$ = 92,000; $R_{2.2}$ = 110,000 | 10 | 16.36 |
| $R_{3.0}$ = 170,000; $R_{3.3}$ = 195,000 | 10 | 12.18 |
| $R_{4.0}$ = 258,000; $R_{4.4}$ = 310,000 | 10 | 16.77 |
| | | 15.31 MEAN |

| V = 10 FPS (6 KTS) | | |
|---|---|---|
| $R_{2.0}$ = 150,000; $R_{2.2}$ = 160,000 | 10 | 6.25 |
| $R_{3.0}$ = 215,000; $R_{3.3}$ = 235,000 | 10 | 8.50 |
| $R_{4.0}$ = 315,000; $R_{4.4}$ = 362,000 | 10 | 12.24 |
| | | 9.24 MEAN |

| V = 5 FPS (3 KTS) | % INC TH | % INC RES |
|---|---|---|
| $R_{2.0}$ = 92,000<br>$R_{2.1}$ = 100,000 | 5 | 8.0 |
| $R_{3.0}$ = 170,000<br>$R_{3.15}$ = 180,000 | 5 | 5.5 |
| $R_{4.0}$ = 258,000<br>$R_{4.2}$ = 285,000 | 5 | 9.5 |
| | | 7.6 MEAN |

| V = 10 FPS (6 KTS) | | |
|---|---|---|
| $R_{2.0}$ = 150,000<br>$R_{2.1}$ = 155,000 | 5 | 3.2 |
| $R_{3.0}$ = 215,000<br>$R_{3.15}$ = 228,000 | 5 | 5.7 |
| $R_{4.0}$ = 315,000<br>$R_{4.2}$ = 340,000 | 5 | 7.3 |
| | | 5.4 MEAN |

2. Run 30

$\sigma_f$ = 20,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .92

| V = 5 FPS | % INC TH | % INC RES |
|---|---|---|
| $R_{1.0}$ = 44,410<br>$R_{1.05}$ = 46,000 | 5 | 3.45 |
| $R_{2.0}$ = 127,200<br>$R_{2.2}$ = 135,000 | 5 | 5.77 |
| $R_{3.0}$ = 240,000<br>$R_{3.15}$ = 257,000 | 5 | 6.60 |
| $R_{4.0}$ = 386,300<br>$R_{4.2}$ = 420,000 | 5 | 8.02 |
| | | 5.96 MEAN |

| V = 10 FPS | % INC TH | % INC RES |
|---|---|---|
| $R_{1.0}$ = 127,500<br>$R_{1.05}$ = 130,000 | 5 | 2.3 |
| $R_{2.0}$ = 173,200<br>$R_{2.1}$ = 187,000 | 5 | 7.3 |
| $R_{3.0}$ = 283,500<br>$R_{3.15}$ = 310,000 | 5 | 8.5 |
| $R_{4.0}$ = 431,200<br>$R_{4.2}$ = 475,000 | 5 | 9.2 |
| | | 6.8 MEAN |

| V = 5 FPS | % INC TH | % INC RES |
|---|---|---|
| $R_{1.0}$ = 44,410<br>$R_{1.1}$ = 50,000 | 10 | 11.18 |
| $R_{2.0}$ = 127,200<br>$R_{2.2}$ = 147,000 | 10 | 13.46 |
| $R_{3.0}$ = 240,000<br>$R_{3.3}$ = 278,000 | 10 | 13.67 |
| $R_{4.0}$ = 386,300<br>$R_{4.4}$ = 450,000 | 10 | 14.15 |
| | | 13.09 MEAN |

| V = 10 FPS | % INC TH | % INC RES |
|---|---|---|
| $R_{1.0}$ = 127,500<br>$R_{1.1}$ = 132,000 | 10 | 3.40 |
| $R_{2.0}$ = 173,200<br>$R_{2.2}$ = 197,000 | 10 | 12.08 |
| $R_{3.0}$ = 283,500<br>$R_{3.3}$ = 330,000 | 10 | 14.09 |
| $R_{4.0}$ = 431,200<br>$R_{4.4}$ = 495,000 | 10 | 12.80 |
| | | 10.59 MEAN |

E. Summary of thickness

1. At low speeds (5 FPS) a 5 percent error in ice thickness will lead to a 7 to 8 percent error in resistance.

2. At higher speeds (10 FPS) a 5 percent error in ice thickness will lead to a 5 to 6 percent error in resistance.

3. At low speeds (5 FPS) a 10 percent error in ice thickness will lead to a 15 percent error in resistance.

4. At high speeds (10 FPS) a 10 percent error in ice thickness will lead to a 9 percent error in resistance.

5. A 25 percent increase in flexural strength has very little effect on the percent error given above.

F. Effect of flexural strength

1. Run 32

$\sigma_f = 12,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 ft | TH = 4 FT | TH = 2 FT | TH = 4 ft |
| R = 76,317 | R = 195,144 | R = 137,017 | R = 249,767 |

2. Run 21

$\sigma_f = 15,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 ft | TH = 4 FT | TH = 2 ft | TH = 4 FT |
| R = 92,500 | R = 258,000 | R = 150,000 | R = 310,000 |

3. Run 30

$\sigma_f = 20,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 127,268 | R = 386,365 | R = 173,169 | R = 431,200 |

4. Run 27

$\sigma_f = 30,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 214,812 | R = 731,220 | R = 234,237 | R = 758,726 |

5. RUN 36

$\sigma_f$ = 14,300 $\sigma_c$ - 50,000 $\mu$ = .2 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 89,165 | R = 242,246 | R = 146,192 | R = 294,426 |

6. RUN 37

$\sigma_f$ = 16,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 99,607 | R = 381,174 | R = 153,616 | R = 331,355 |

Calculation Data

| % INC $\sigma_f$ | % IN R | SPEED* | THICKNESS* |
|---|---|---|---|
| 5% (14.3K to 15K) | 3.6 | L | L |
| | 6.1 | L | H |
| | 2.5 | H | L |
| | 5.0 | H | H |
| 10% (14.3K to 16K) | 10.0 | L | L |
| | 13.8 | L | H |
| | 4.8 | H | L |
| | 11.14 | H | H |
| 20% (12K to 15K) | 17.5 | L | L |
| | 24.4 | L | H |
| | 8.7 | H | L |
| | 19.4 | H | H |
| 25% (15K to 20K) | 27.3 | L | L |
| | 33.2 | L | H |
| | 13.4 | H | L |
| | 28.1 | H | H |

*L in speed column refers to the low speed range, H refers to the higher speeds used in the sample calculations. The same is true for the thickness used. The exact number can be found by referring to the above sample calculations.

G. Summary of flexural strength

The effect of flexural strength is related to the speed of the vessel and the thickness of the ice. As shown in the accompanying example calculations, the greatest effect occurs at low speed, high thickness. In this case a 5 percent error in measuring flexural strength will lead to a 6.1 percent error in resistance. At high speeds with low thicknesses the results show an opposite trend, i.e., 5 percent error in measuring flexural strength will lead to a 2.5 percent error in resistance.

It should be noted that the results presented here are from Milano's

(1972) program and show a slightly stronger dependence of resistance and flexural strength than shown by Lewis (1972) and Vance (1974). This fact should be kept in mind when utilizing the data presented herein.

H. Effect of ice specific gravity

1. RUN 28

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .82

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 106,971 | R = 304,183 | R = 162,786 | R = 355,560 |

2. RUN 21

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 92,500 | R = 258,000 | R = 150,000 | R = 310,000 |

3. RUN 33

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .966

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 86,900 | R = 235,722 | R = 142,715 | R = 287,099 |

Calculation Data

| % INC SG | % DEC R | SPEED | THICKNESS |
|---|---|---|---|
| 10% (.82 to .92) | 15.6 | L | L |
| | 17.9 | L | H |
| | 8.5 | H | L |
| | 14.7 | H | H |
| 5% (.96 to .966) | 6.4 | L | L |
| | 9.4 | L | H |
| | 5.1 | H | L |
| | 8.0 | H | H |
| 15% (.82 to .966) | 23.1 | L | L |
| | 29.0 | L | H |
| | 14.1 | H | L |
| | 23.8 | H | H |

I. Summary of specific gravity

Although the specific gravity of the ice falls within small limits, i.e., .89 to .94 with a mean of .92, errors made in measuring the S.G. will have a large effect on the calculation of the resistance of the vessel. This is particularly

true at low speeds and high thicknesses, which one would suspect, for it is in this operational mode that the energy utilized to submerge the ice is the greatest percentage of the overall resistance. However, one should be aware, the thicker the ice the greater the impact of the specific gravity of the ice.

The sample calculations using Milano's program indicate a 5 percent error in S.G. will lead to a 9.4 percent error in resistance at the worst condition. A 15 percent error in S.G. will lead to a 20 percent error in resistance at the worst condition.

J. Effect of velocity

1. Run 21

$\sigma_f = 15{,}000$ $\sigma_c = 50{,}000$ $\mu = .2$ SG = .92

| TH = 1 FT | % INC VEL | % INC R |
|---|---|---|
| 5-7 FPS | 30 | 36 |
| 7.5-10 FPS | 25 | 40 |
| 9.5-10 FPS | 10 | 18 |
| 9.5-10 FPS | 5 | 6.4 |
| **TH = 2 FT** | | |
| 5 - 7 | 30 | 16.3 |
| 7.5 - 10 | 25 | 23.3 |
| 9 - 10 | 10 | 12.0 |
| 9.5 - 10 | 5 | 6.7 |
| **TH = 4 FT** | | |
| 5 - 7 | 30 | 6.5 |
| 7.5 - 10 | 25 | 9.0 |
| 9 - 10 | 10 | 2.9 |
| 9.5 - 10 | 5 | 1.6 |
| **TH = 6 FT** | | |
| 5 - 7 | 30 | 3.1 |
| 7.5 - 10 | 25 | 5.3 |
| 9 - 10 | 10 | 2.1 |
| 9.5 - 10 | 5 | 1.3 |

2. RUN 30

$\sigma_f = 20{,}000$ $\sigma_c = 50{,}000$ $\mu = .2$ SG = .92

| TH = 1 FT | % INC VEL | % INC R |
|---|---|---|
| 5 - 7 | 30 | 35.8 |
| 7.5 - 10 | 25 | 39.1 |
| 9 - 10 | 10 | 17.3 |
| 9.5 - 10 | 5 | 8.6 |

| TH = 2 FT | % INC VEL | % INC R |
|---|---|---|
| 5 - 7 | 30 | 9.4 |
| 7.5 - 10 | 25 | 16.6 |
| 9 - 10 | 10 | 7.9 |
| 9.5 - 10 | 5 | 3.9 |
| **TH = 4 FT** | | |
| 5 - 7 | 30 | 4.4 |
| 7.5 - 10 | 25 | 4.9 |
| 9 - 10 | 10 | .9 |
| 9.5 - 10 | 5 | .5 |
| **TH = 6 FT** | | |
| 5 - 7 | 30 | 10 |
| 7.5 - 10 | 25 | 3.4 |
| 9 - 10 | 10 | 1.5 |
| 9.5 - 10 | 5 | .7 |

K. Summary of velocity effect

The effect of velocity is more pronounced at low thickness and in we[illegible]r ice as one would suspect. The sample calculations indicate a 10 percent error in velocity measurements will lead to an 18 percent error in resistance in one foot of ice. In 2 feet of ice a 10 percent error in velocity will lead to a 12 percent error in resistance. In 6 feet of ice when other resistance components predominate, a 10 percent error in velocity measurement will only cause a 2 percent error in resistance.

The interaction of the various components can be seen from the decrease in velocity effect where the flexural strength is increased. The 25 percent increase in strength causes a decrease in the effect of velocity on the resistance.

The importance of accurately measuring velocity is not only emphasized by the errors pointed out herein, but in addition, the velocity of the ship is utilized directly when making power calculations from machinery readouts.

L. Effect of compressive strength ($\sigma_c$)

1. Run 35

$\sigma_f$ = 15,000 $\sigma_c$ = 45,000 $\mu$ = .2 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 94,579 | R = 261,071 | R = 105,394 | R = 312,448 |

2. Run 21

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 93,000 | R = 258,000 | R = 150,000 | R = 310,000 |

3. RUN 34

$\sigma_f$ = 15,000 $\sigma_c$ = 52,500

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 92,829 | R = 256,421 | R = 148,644 | R = 307,798 |

4. RUN 17

$\sigma_f$ = 15,000 $\sigma_c$ = 100,000

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 4 FT | TH = 4 FT |
| R = 86,813 | R = 240,437 | R = 142,628 | R = 291,814 |

Calculation Data

| RUN | % INC $\sigma_c$ | % INC R | SPEED | THICKNESS |
|---|---|---|---|---|
| (34-21) | 5% | .2 | L | L |
| | | .6 | L | H |
| | | .9 | H | L |
| | | .7 | H | H |
| (21-35) | 10% | 1.7 | L | L |
| | | 1.2 | L | H |
| | | .3 | H | L |
| | | .8 | H | H |
| (34-35) | 15% | 1.8 | L | L |
| | | 1.8 | L | H |
| | | 1.2 | H | L |
| | | 1.5 | H | H |
| (21-17) | 50% | 6.6 | L | L |
| | | 6.8 | L | H |
| | | 4.9 | H | L |
| | | 5.9 | H | H |

M. Summary of compressive strength effect

Small changes in the compressive strength of the ice has very little effect on the resistance predicted. It is not until we encounter errors in the range of 50 to 60 percent do we see a 5 to 6 percent change in resistance.

For all practical purposes, acceptable values of compressive strength of ice presented in the literature can be used without any significant effect on the resistance prediction.

N. Effect of friction ($\mu$)

1. RUN 39

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .1 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 78,533 | R = 206,913 | R = 140,948 | R = 262,825 |

2. RUN 21

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH= 2 FT | TH = 4 FT |
| R = 92,500 | R = 258,000 | R = 150,000 | R = 310,000 |

3. RUN 40

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .1 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | V = 4 FT |
| R = 100,786 | R = 283,325 | R = 153,301 | R = 332,435 |

4. RUN 41

$\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .235 SG = .92

| | | | |
|---|---|---|---|
| V = 5 FPS | V = 5 FPS | V = 10 FPS | V = 10 FPS |
| TH = 2 FT | TH = 4 FT | TH = 2 FT | TH = 4 FT |
| R = 98,561 | R = 275,684 | R = 152,066 | R = 325,474 |

RUN 39 (.1) - 21 (.2) 50% RUN 21 (.2) - 41 (.235) 15%
RUN 21 (.2) - 40 (.25) 20% RUN 41 (.235) - 40 (.25) 6%

Calculation Data

| % INC $\mu$ | % INC R | SPEED | THICKNESS |
|---|---|---|---|
| 6% (41-40) | 2.2 | L | L |
| | 2.7 | L | H |
| | .8 | H | L |
| | 2.1 | H | H |
| 15% (21-41) | 6.1 | L | L |
| | 6.4 | L | H |
| | 1.4 | H | L |
| | 4.8 | H | H |
| 20% (21-40) | 8.2 | L | L |
| | 8.9 | L | H |
| | 2.1 | H | L |
| | 6.7 | H | H |

Calculation Data (Continued)

| % INC $\mu$ | % INC R | SPEED | THICKNESS |
|---|---|---|---|
| 50% (39-21) | 15.1 | L | L |
| | 19.8 | L | H |
| | 6.0 | H | L |
| | 15.2 | H | H |

O. Summary of friction effect

The effect of the coefficient of friction (defined as the normal force divided by the tangetral force, for the lack of any better understanding of the phenomenon) is difficult to appreciate. If one is dealing with dynamic friction, the coefficient can vary from .025 to as high as .5. Most of the published data confines the range from .1 to .3.

Milano's program indicates that for small changes in the friction coefficient, i.e., 6 percent (.235 to .25) there is only a small effect on the overall resistance, i.e., 3 percent. However a 50 percent increase, .1 to .2, could cause a 70 percent error in the resistance estimate.

Recent model tests (Lecourt, 1975) have indicated that an increase in the coefficient from .037 to .28 (7.5 fold increase) has lead to a 40 percent increase in resistance. Full scale tests run by the Wartrila Shipyard in Finland (Makimer, 1975) have indicated a 30 percent decrease in resistance of the ice-breaking vessel SILMA after being coated with a low friction coating. Unfortunately, no friction measurements were taken on the vessel.

In summary, it can be said that small errors in measuring the friction coefficient, i.e., ±10 percent, will have only a minor effect on the resistance prediction, however, one must know or have some good idea of what the friction coefficient is, i.e., .10 or .20.

P. Effect of propulsion equipment measurements

From the equations in the next section, it can be seen that the relationship between the measured parameters and the computed resistance in a linear one and any error made in measuring the parameter, i.e., torque, RPM, velocity or propulsive coefficient (which is estimated from the model tests) will result in an error of equal magnitude in computing the resistance. Several examples of typical values are presented.

Q. Equations

1. Effect of thrust

$$\text{RESISTANCE} = \text{THRUST}_{(\text{AT SHAFT})} \times \text{P.C.}$$

@ 13 FPS 4' THICKNESS R = 338,633

$$\text{THRUST} = \frac{R}{\text{P.C.}} = \frac{338633}{.6} = 564{,}388$$

| | % INC $T_{SHAFT}$ | % INC R |
|---|---|---|
| $T_{SHAFT}$ = 564,388 | | |
| P.C. = .6 | 5 | 5 |
| RESIS = 338,632 | (T =564388-T=536000) | |
| $T_{SHAFT}$ = 536,000 | | |
| P.C. = .6 | 10 | 10.2 |
| RESIS = 321,600 | (T=564388-T=507000) | |
| $T_{SHAFT}$ = 507,000 | | |
| P.C. = .6 | | |
| RESIS = 304,200 | | |
| $T_{SHAFT}$ = 564,388 | 5 | 5 |
| P.C. = .6 | (P.C.=.6=P.C.+.57) | |
| RESIS = 338,632 | | |
| $T_{SHAFT}$ = 564,388 | 10 | 10 |
| P.C. = .57 | (P.C.=.6-P.C.=.54) | |
| RESIS = 321,701 | | |
| $T_{SHAFT}$ =564,388 | | |
| P.C. = .54 | | |
| RESIS = 304,769 | | |

2. Effect of torque

$$SHP = \frac{R \pi Q N}{550}$$

$$EHP = SHP \times P.C.$$

$$RESISTANCE = \frac{EHP \times 550}{V}$$

$$RESISTANCE = \frac{2 \pi QN\ P.C.}{V}$$

| | | |
|---|---|---|
| Vel. - | FACTOR/ERROR | FACTOR/ERROR |
| | P.C. = .6 | N = 2.92 RPS |
| 5-7 FPS | 5% .57 | 5% 2.77 RPS |
| 7.5 - 10 FPS | 10% .54 | 10% 2.63 RPS |
| 9 - 10 FPS | | |
| 9.5 - 10 FPS | | |

RUN 21 13 FPS 4' ICE: $EHP = \frac{RES \times VEL}{550} = \frac{338633 \times .3}{550} = 8004$

$$SHP = \frac{EHP}{P.C.} = \frac{8004}{.6} = 13340$$

$$Q = \frac{550 \times SHP}{2\pi N} = \frac{(550)(13340)}{2\pi\ (2.92)} = 399904$$

| | | |
|---|---|---|
| Q = 399904 | % INC Q | % INC R |
| N = 2.92 RPS | 5 | 4.9 |
| V = 5 FPS | (Q=399904-Q=380000) | |
| P.C. = .6 | | |
| R = 880428 | 10 | |
| Q = 380000 | (Q=399904-Q=360000) | 9.9 |
| N = 2.92 RPS | | |
| V = 5 FPS | | |
| P.C. = .6 | | |
| R = 836608 | | |
| Q = 360000 | | |
| N = 2.92 RPS | | |
| V = 5 FPS | | |
| P.C. = .6 | | |
| R = 792576 | | |
| Q = 399904 | % INC N | % INC R |
| N = 2.92 RPS | 5 | 5.1 |
| V = 5 FPS | (N=2.92 - N=2.77) | |
| P.C. = .6 | | |
| R = 880438 | 10 | |
| Q = 399904 | (N=2.92 - N=2.63) | 9.9 |
| N = 2.77 RPS | | |
| V = 5 FPS | | |
| P.C. = .6 | | |
| R = 835210 | | |
| Q = 399904 | | |
| N = 2.63 RPS | | |
| V = 5 FPS | | |
| P.C. = .6 | | |
| R = 792997 | | |
| Q = 399904 | % INC P.C. | % INC R |
| N = 2.92 | 5 | 5 |
| V = 5 FPS | (P.C.=.6 - P.C.=.57) | |
| P.C. = .6 | | |
| R = 880439 | 10 | 10 |
| Q = 399904 | (P.C.=.6 - P.C.=.54) | |
| N = 2.92 | | |
| V = 5 FPS | | |

P.C. = .57
R = 836417
Q = 399904
N = 2.92
V = 5 FPS
P.C. = .54
R = 792395

$$R = \frac{2\pi QN\ P.C.}{V}$$

Q = 399904 N = 2.92 P.C. = .6

| VEL | % INC VEL | RESISTANCE | % INC R |
|---|---|---|---|
| 5 - 7 | 30 | 880439<br>628885 | 28.5 |
| 7.5 - 10 | 25 | 586959<br>440219 | 25 |
| 9 - 10 | 10 | 489133<br>440219 | 10 |
| 9.5 - 10 | 5 | 463389<br>440219 | 5 |

R. Electrical power measurement

By noting voltage and amperage to the motor, a rough estimate of the power being used can be obtained.

$$P = E\ I \text{ watts}$$

$$SHP = \text{watts}/746$$

$$\text{RESISTANCE} = \frac{EHP \times 550}{V}$$

$$= \frac{EI \times 550\ P.C.}{746\ V}$$

$$\text{RESISTANCE} = \frac{.7372\ EI\ P.C.}{V}$$

Thus, as in the previous equations, due to the linear relationship between power and resistance, an error in measuring voltage or amperage would lead to an equal percentage error in the resistance computed.

S. Summary of propulsion equipment

It is evident from the equations presented here and in other sections of this report that the relationship between propulsion equipment measurements, i.e., torque, thrust, volts, amps, RPM and the prediction, or in this case, the calculation of resistance, is a direct one. That is, any error made in measuring these parameters leads to an error of equal magnitude in the resistance calculated.

T. Effect of draft

1. RUN 45 $\sigma_f$ = 15,000 $\sigma_c$ = 50,000 $\mu$ = .2 SG - .92 DR 28

2. RUN 44 $\sigma_f = 15,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92 DR 30

THICKNESS = 2 FT

| VEL | RESISTANCE (45) | RESISTANCE (44) | % DIFF |
|---|---|---|---|
| 5 | 95,440 | 92,088 | 3.5 |
| 10 | 149,259 | 144,460 | 3.2 |
| 15 | 261,422 | 253,155 | 3.1 |
| 20 | 425,813 | 411,587 | 3.3 |

THICKNESS = 4 FT

| VEL | RESISTANCE (45) | RESISTANCE (44) | % DIFF |
|---|---|---|---|
| 5 | 266,586 | 251,771 | 5.5 |
| 10 | 313,702 | 293,055 | 6.6 |
| 15 | 369,833 | 345,800 | 6.4 |
| 20 | 486,721 | 454,911 | 6.5 |

THICKNESS = 6 FT

| VEL | RESISTANCE (45) | RESISTANCE (44) | % DIFF |
|---|---|---|---|
| 5 | 585,930 | 558,699 | 4.6 |
| 10 | 642,720 | 611,227 | 4.8 |
| 15 | 698,052 | 656,581 | 5.9 |
| 20 | 771,628 | 724,291 | 6.1 |

U. Summary of draft effect

The change in draft of the POLAR STAR from 28 feet to 30 feet changes many of the parameters that enter the icebreaking prediction equation, i.e., displacement changes from 10,860 tons to 12,200 tons, the bow angle change from 15° to 14.5°, etc. Therefore, a whole new data set was used in Dr. Milano's program for a draft of 30 feet (see Appendix B). The results of the comparison indicate that when the draft is increased to 30 feet, the overall ice resistance decreased from 3 to 6 percent with the larger percentages at the higher ice thicknesses. See Figure 8.

In addition to the icebreaking capability, there are two other aspects of increased draft that must be kept in mind. Once is the effect on the extractor difficulty encountered; this effect will be covered in the Ramming and Extractor Prediction aspect. The record aspect is the decreased clearance (overhang) caused by increased draft. The POLAR STAR was designed with a vertical clearance of 5 feet between the 28 foot waterline and the start of the curvature of the stern to the vertical. The increased draft would decrease this clearance to approximately 3 feet.

## VI. RAMMING AND EXTRACTION PREDICTIONS FOR THE POLAR STAR BY CDR G. P. VANCE

### A. Abstract

This report contains predictions for the POLAR STAR in the ramming mode. The calculations indicate that the POLAR STAR would be capable of breaking almost 21 feet of homogenous ice in ramming (see Appendix C).

Utilizing the theory available the extraction difficulty is also predicted.

### B. Introduction

The prediction of a vessel's capability to break ice in the ramming mode,

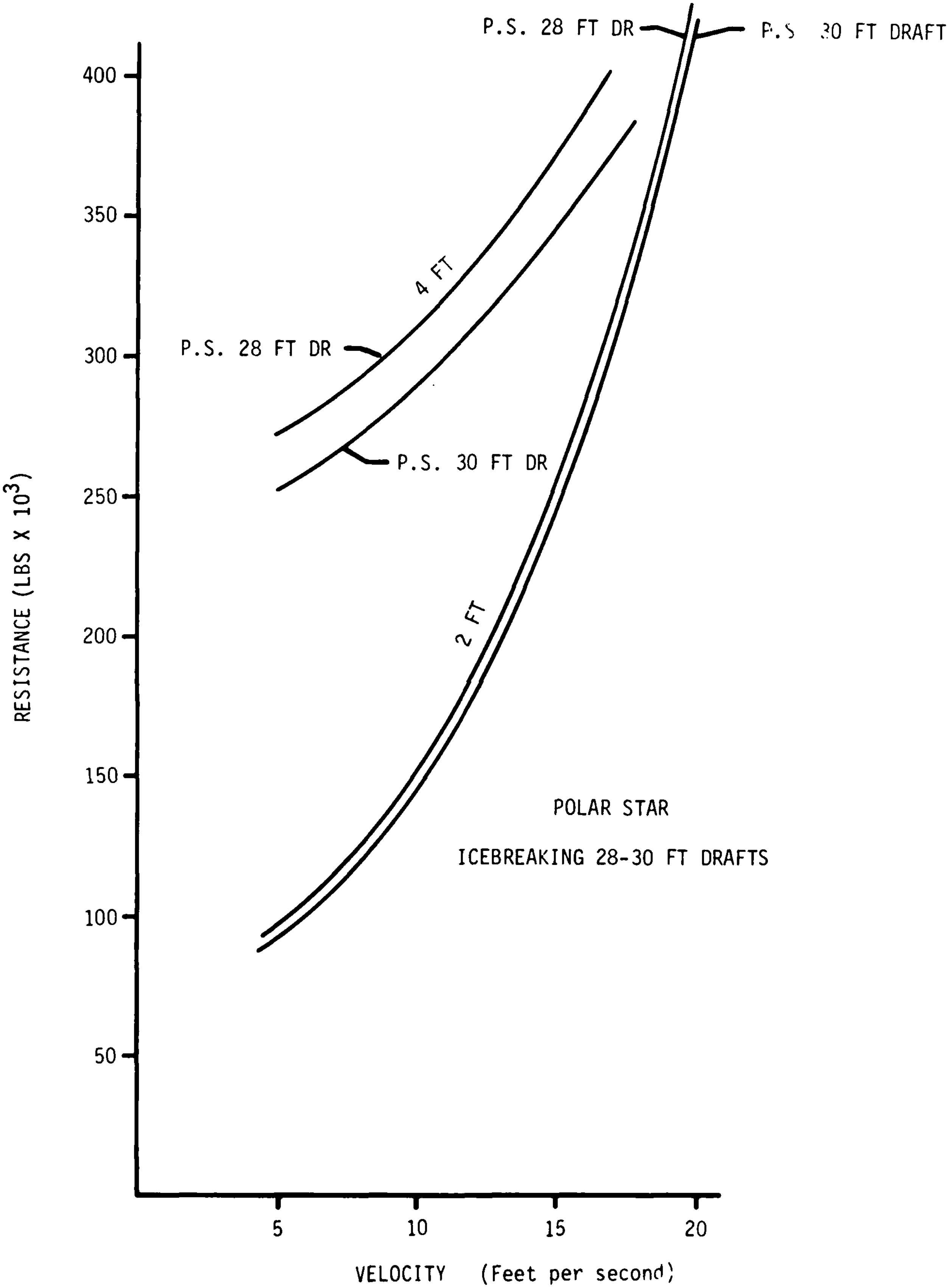

P.S. 28 FT DR
P.S. 30 FT DRAFT
400
350
300
250
200
150
100
50
RESISTANCE (LBS X $10^3$)
4 FT
P.S. 28 FT DR
P.S. 30 FT DR
2 FT
POLAR STAR
ICEBREAKING 28-30 FT DRAFTS
5
10
15
20
VELOCITY (Feet per second)

Figure 8

i,e., backing up and ramming into the ice and coming to a complete stop, has been attempted by White (1969) and modified by Lewis (1970). The method assumes a rigid flat sheet of homogenous ice with a specified tensile strength. The vessel rides up on the ice sheet and exerts a downward force on the ice until failure occurs. The downward force generated is a function of the surge, heave and pitch motions of the ship and the impact velocity and displacement of the ship (see Fig. 9).

White assumed a realtively simple relationship between the downward force exerted to break the ice and Lewis introduced some field data to refine the force equation.

The extraction difficulty is a more elusive number to pin down. White assumed that the extraction difficulty was a function of the downward force, the coefficient of static friction and the bow angles. He then formed a ratio of the thrust needed to extract the vessel from the ice and the bollard foreward thrust available from the vessel. This "Difficulty of Extraction Ratio" was not an absolute number, i.e., it was a number one could compare to other vessels such as the WIND class and the GLACIER.

This report presents calculations made for the POLAR STAR.

Where:
- $B$ = maximum beam in feet
- $d$ = draft of the vessel in feet
- $C_W$ = water plane area coefficient
- $C_b$ = block coefficient
- $SA$ = spread angle complement in radians
- $f_k$ = coefficient of kinetic friction (assumed to be .2 for uniformity)
- $BA$ = bow angle in radians

Figure 9 is a plot of the predicted ice thickness that can be broken by the POLAR STAR. The sample calculations are shown in the appendices. It should be noted the plot reflects a 28 foot draft and $\sigma_f$ = 235 PSI.

Lewis (1970) has indicated that k = .45 used by White may have been too low and recommends a figure of k = 1.02 from full scale tests, he also indicates that a $\sigma_f$ = 235 PSI may be too high and a more realistic figure would be in the area of 100 to 140 PSI.

C. Ramming capability

The equations used in predicting the thickness of ice by White are:

$$F_{BZR} = k \cdot \sigma \cdot t^2$$

substituting value of .45 for k and 235 PSI for the tensile (flexural) strength of ice:

$$t_r = \frac{F_{BZR}}{100}$$

where "$t_r$" stands for thickness of standard ice broken due to ramming, in inches, and "$F_{BRZ}$" is the relatively sustained downward force against the ice in pounds. This last parameter "$F_{BRZ}$" further depends on three factors: impact velocity "v" in FPS, ship displacement "$\Delta$" in pounds, and the White Ratio "WR". The equation for calculating "$F_{BRZ}$" is as follows:

$$F_{BZR} = 6.64\ V_j\ (WRX\Delta)^{0.845}$$

PREDICTION OF THICKNESS OF STANDARD SEA ICE BROKEN
AS A RESULT OF RAMMING AS A FUNCTION OF IMPACT VELOCITY

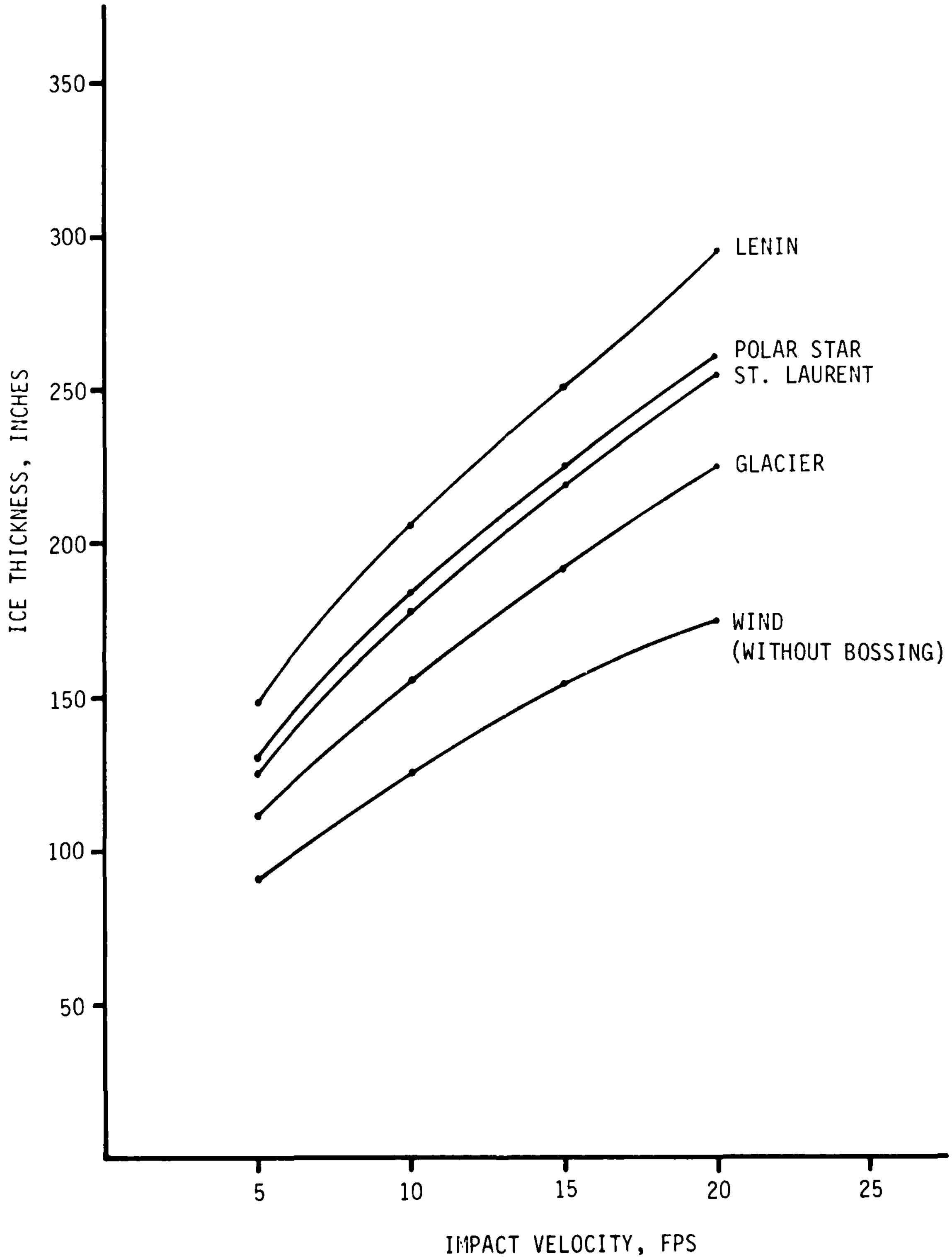



Figure 9.

The White Ratio is a coefficient of performance that was developed by White, in his study of the mechanics of icebreaking. The equation used to obtain this numbers is:

$$WR = 1.000234(10.72+{}^{B}/d)(0.1833+C_W)(1.652-C_b) \times (6.14-SA^2)(0.725-f_k)(1.718-BA)$$

The recommended equations would be:

$$F_{BRZ} = 1.02\ \sigma_f t^2 \quad \text{or}$$

$$t_r = \frac{F_{BZR}}{106.25}$$

i.e., $\sigma_f$ 104.16 PSI $\cong$ 15000 PSF $\cong$ 7.32 kg/cm$^2$

D. Extraction difficulty

White (1969) has proposed an index of extraction difficulty that reflects a computed extraction thrust based on the hull form and coefficient of static friction divided by the maximum bollard thrust available. This ratio is more of a comparison to other vessels rather than an exact indication of the thrust available or necessary to extract the vessel after ramming. Figure 10 shows the computed index of extraction for several icebreakers and that of the POLAR STAR. The POLAR STAR curve is presented for a bow angle of 15° and a bow angle of 30°. The equations are very sensitive to the bow angle and this fact is reflected in the careful design of the POLAR STAR bow. The POLAR STAR has a bow angle of 15° at the 28 foot water line this angle gradually increases to 30° at the 18 foot water line where it is carried to a 6 foot vertical step. Thus when computing the extraction difficulty one must determine how far the ship will penetrate the ice to determine its extraction difficulty. In most instances of ramming the momentum of the vessel will be sufficient to carry it to a trim of 1° or 2° which will insure a bow angle of greater than 15° and close to 30°. Thus the POLAR STAR should not encounter any unusual difficulty in extracting itself from a ram (Fig. 10).

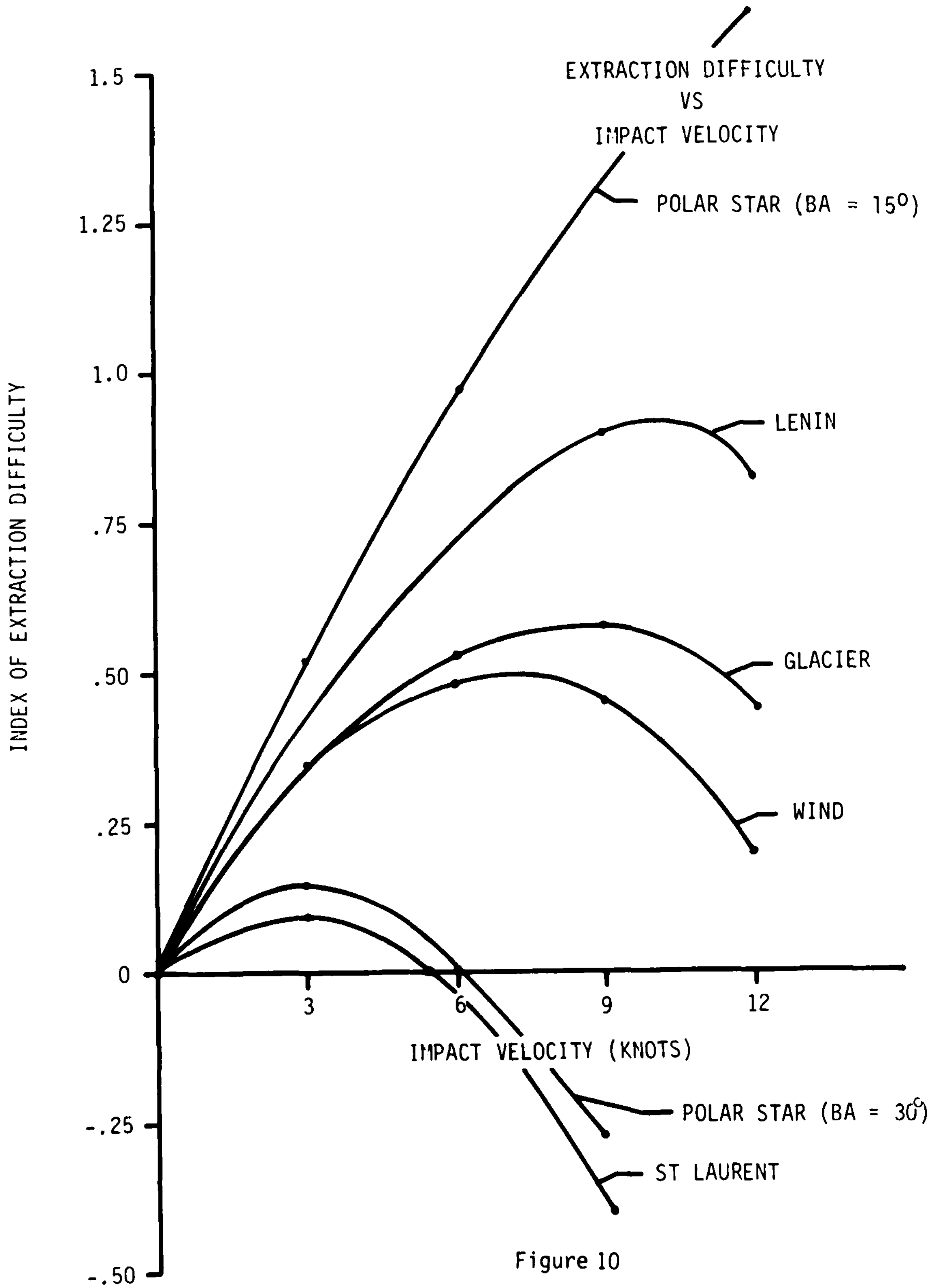

EXTRACTION DIFFICULTY
VS
IMPACT VELOCITY
1.5
1.25
1.0
.75
.50
.25
0
-.25
-.50
INDEX OF EXTRACTION DIFFICULTY
POLAR STAR (BA = 15°)
LENIN
GLACIER
WIND
POLAR STAR (BA = 30°)
ST LAURENT
3
6
9
12
IMPACT VELOCITY (KNOTS)

Figure 10

## VII. REFERENCES


Edwards, R.Y., et al., (1972), "Full Scale and Model Tests of Great Lakes Icebreakers," SNAME ________ volume 80.

Enkvist, E., (1972), "On the Ice Resistance Encountered by Ship's Operating in the Continuous Mode of Icebreaking," Wartsila, 4 elsinki.

Kasteljan, V.I., et al., (1968), "Ice Resistance to Motions of a Ship," Sudostroyenize Leningrad.

Lasky, M.P., et al., (1971), "Powering Predictions and Flaw Observations for the United States Coast Guard Proposed Icebreaker Design (M-14-3) Model 5249," NSRDC Report P-223-H-09, April.

Lecourt, E.J., (1975), "Icebreaking Model Tests of the 140 Foot WYTM," CG R&D report, June.

Lewis, J.W., et al., (1970), "Methods of Predicting Icebreaking Resistance and Ice Resistance Characteristics of Icebreakers," Transaction SNAME.

Lewis, J.W., et al., (1971), "Methods of Predicting Icebreaking and Ice Resistance Characteristics of Icebreakers," SNAME paper, vol. 79.

Lewis, J.W., (1972), "Ship Model Ice Resistance Experiments," CG R&D report project 731342, December.

Makimer, E., (1975), "Influence of Friction on Ice Resistance - Search for a Low Friction Surface," päper presented at Eastern Canadian Section SNAME, Ice Tech 1975, April.

Milano, V.R., (1972), "Ship Resistance to Continuous Motion in Ice," Ph.D dissertation, Stevens Institute of Technology.

Milano, V.R., (1973), "Ship Resistance to Continuous Motion in Ice," SNAME paper, vol. 81.

Milano, V.R., (1975), "Ship Resistance to Continuous Motion in Ice," SNAME paper, IceTech 75.

Vance, G.P., (1974), "A Modeling System for Vessels in Ice," Ph.D Dissertation, University of Rhode Island.

White, R.M., (1969), "Prediction of Icebreaker Capabilities," Transaction of the Royal Institute of Naval Architects, Paper W8.

# APPENDICES

A. Curves of Resistance versus Velocity and Thrust versus Velocity

B. POLAR STAR 30 ft Draft Particulars

C. Sample Calculation

D. Literature Citations and Selected Bibliography

# APPENDIX A

## Curves of Resistance versus Velocity and Thrust versus Velocity

APPENDIX A: CURVES OF RESISTANCE VERSUS VELOCITY AND THRUST VERSUS VELOCITY

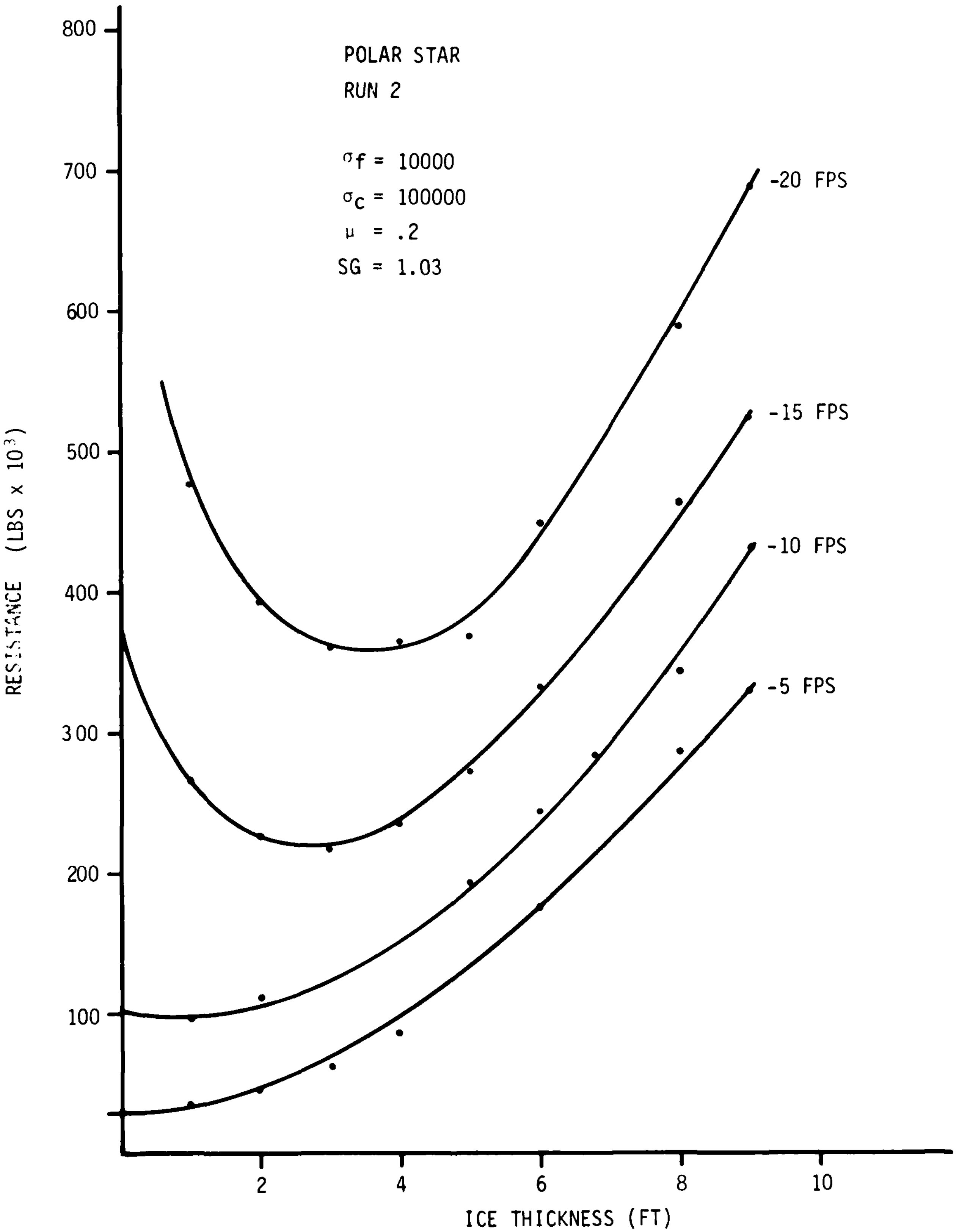



Figure 11.

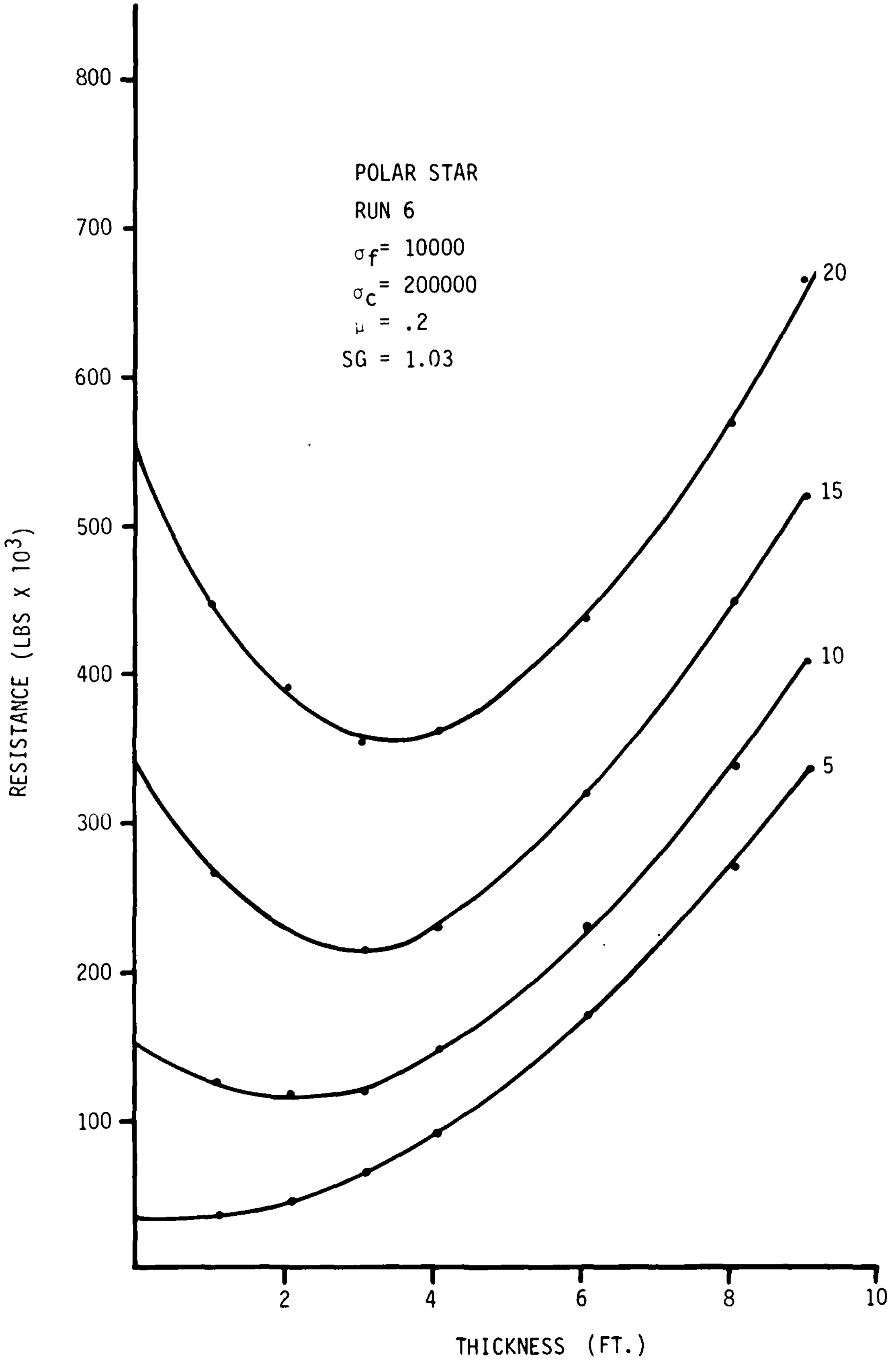

POLAR STAR
RUN 6
$\sigma_f = 10000$
$\sigma_c = 200000$
$\mu = .2$
SG = 1.03
RESISTANCE (LBS X $10^3$)
800
700
600
500
400
300
200
100
2
4
6
8
10
THICKNESS (FT.)
20
15
10
5

Figure 12.

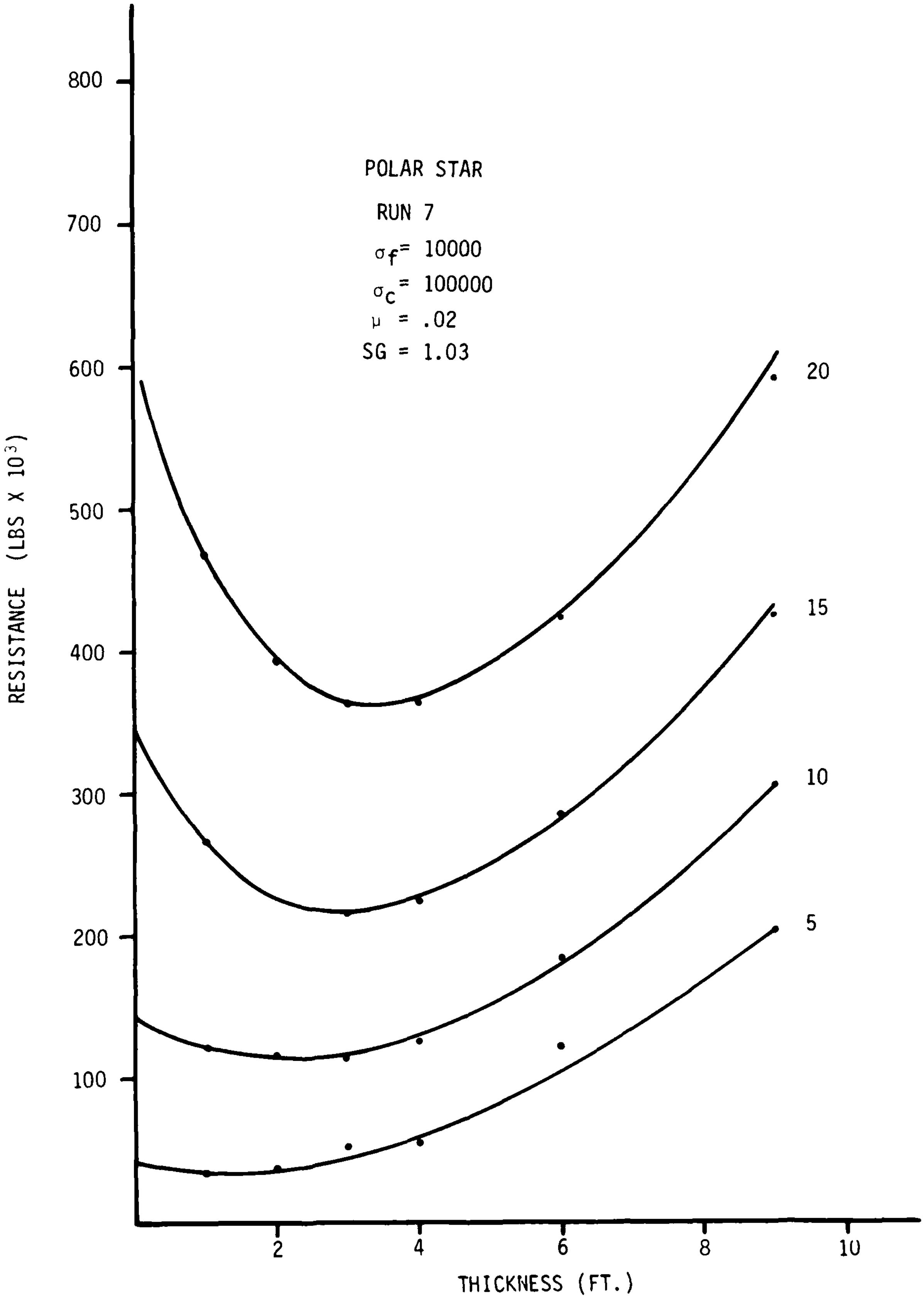

POLAR STAR
RUN 7
$\sigma_f = 10000$
$\sigma_c = 100000$
$\mu = .02$
SG = 1.03
RESISTANCE (LBS X $10^3$)
800
700
600
500
400
300
200
100
2
4
6
8
10
THICKNESS (FT.)
20
15
10
5

Figure 13.

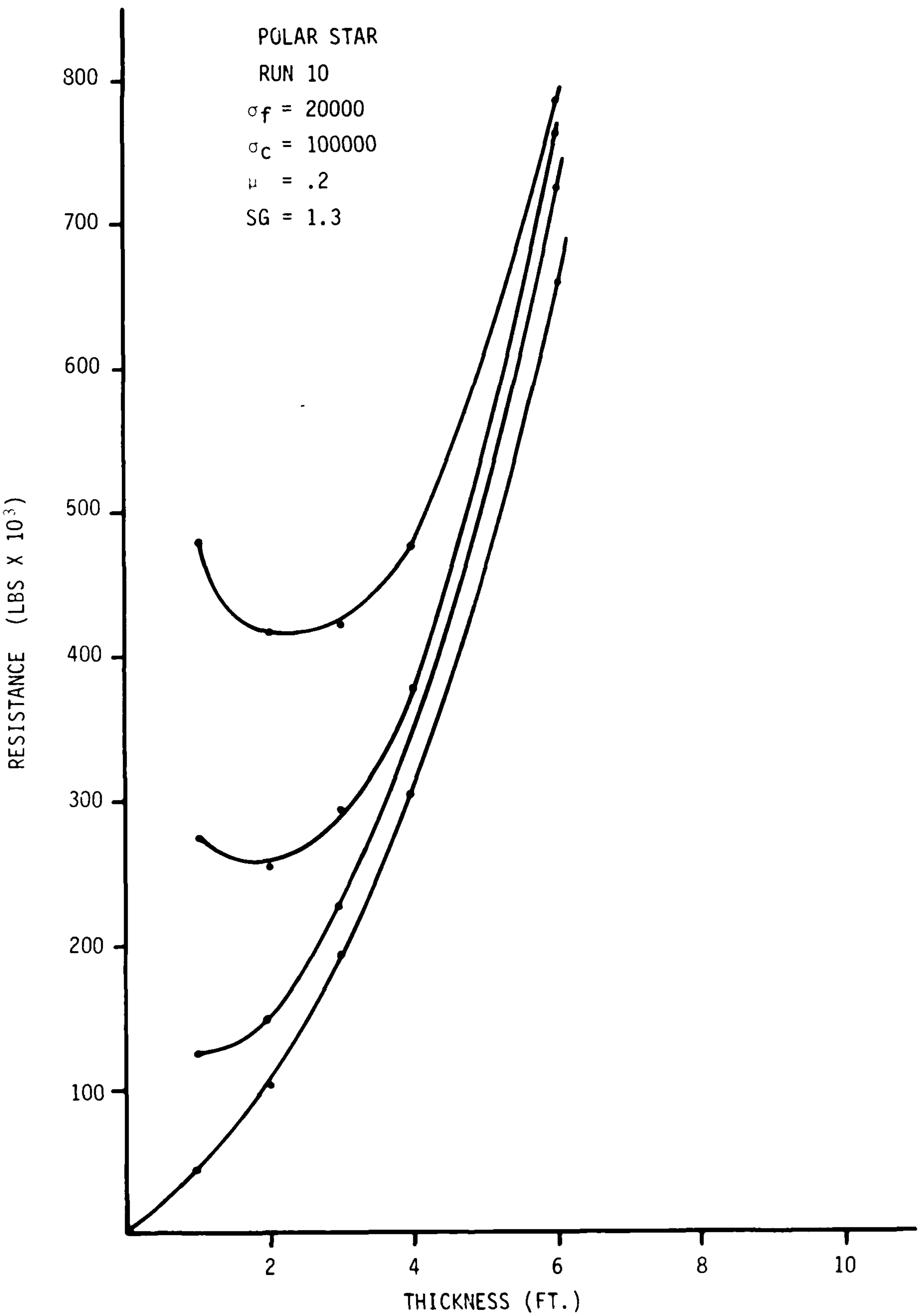

POLAR STAR
RUN 10
$\sigma_f$ = 20000
$\sigma_c$ = 100000
$\mu$ = .2
SG = 1.3
RESISTANCE (LBS X $10^3$)
800
700
600
500
400
300
200
100
2
4
6
8
10
THICKNESS (FT.)

Figure 14

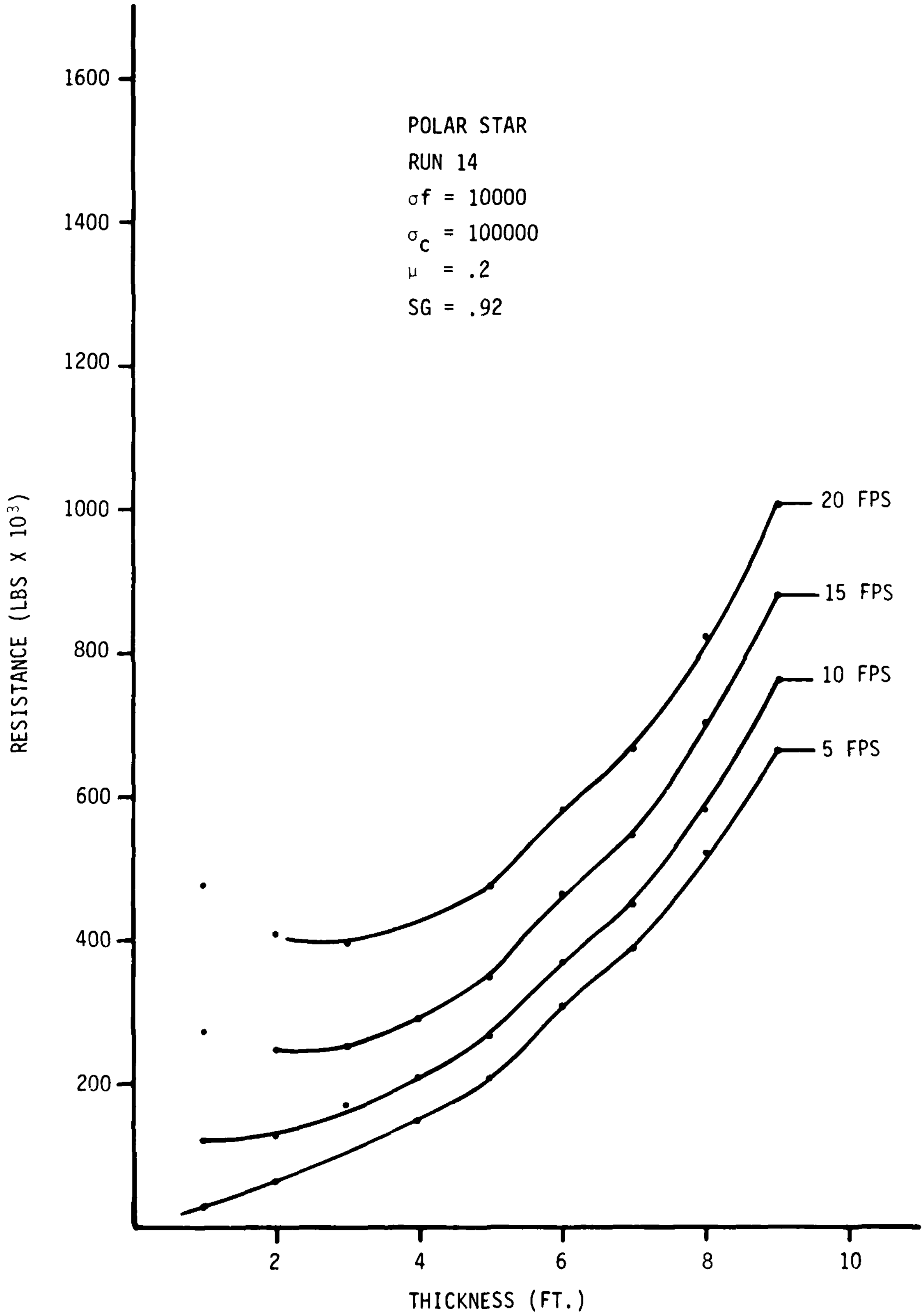
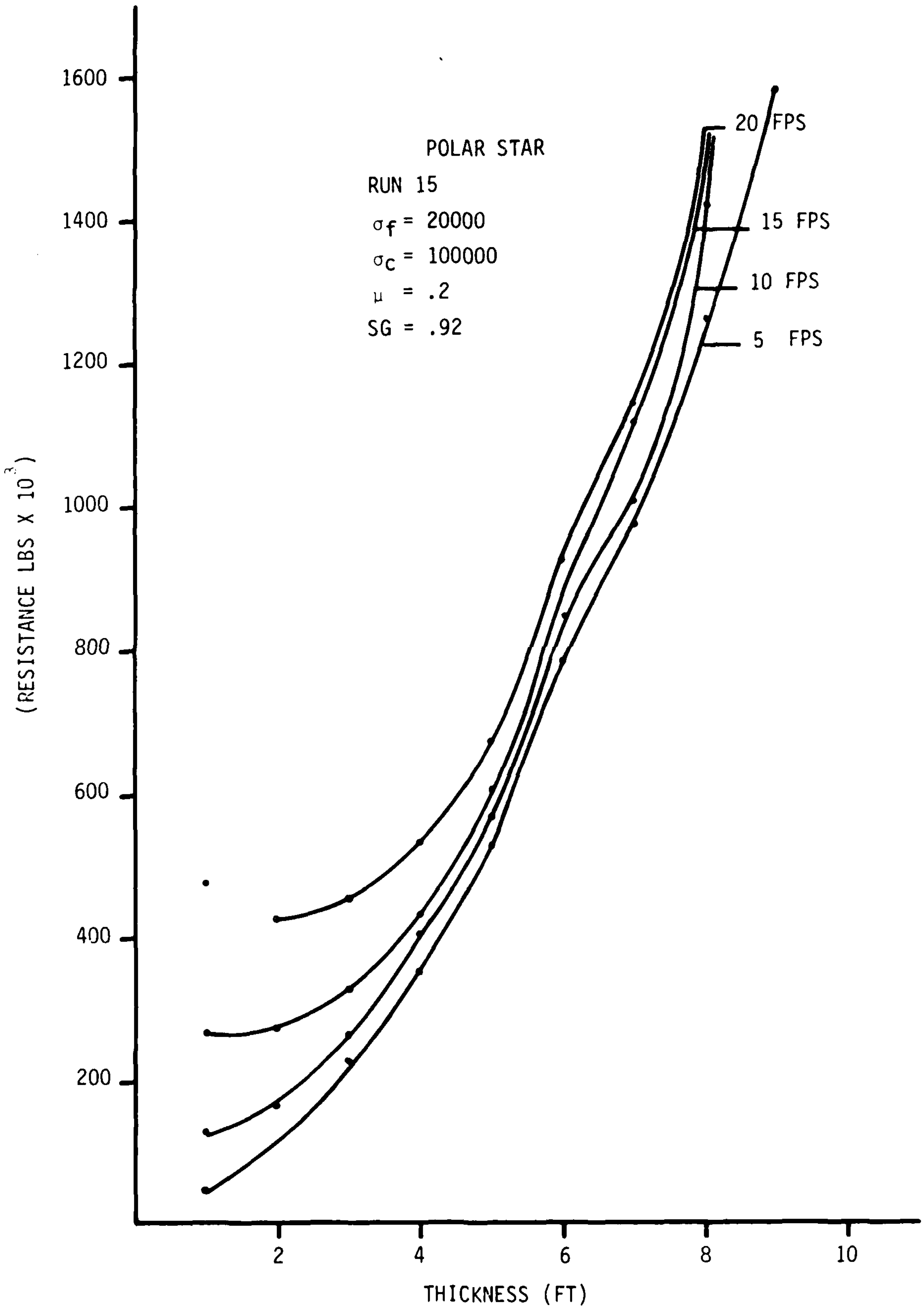

POLAR STAR
RUN 14
σf = 10000
σc = 100000
μ = .2
SG = .92
RESISTANCE (LBS X 10³)
1600
1400
1200
1000
800
600
400
200
20 FPS
15 FPS
10 FPS
5 FPS
2
4
6
8
10
THICKNESS (FT.)

Figure 15



POLAR STAR
RUN 15
$\sigma_f$ = 20000
$\sigma_c$ = 100000
$\mu$ = .2
SG = .92
20 FPS
15 FPS
10 FPS
5 FPS
1600
1400
1200
1000
800
600
400
200
(RESISTANCE LBS X $10^3$)
2
4
6
8
10
THICKNESS (FT)


Figure 16.

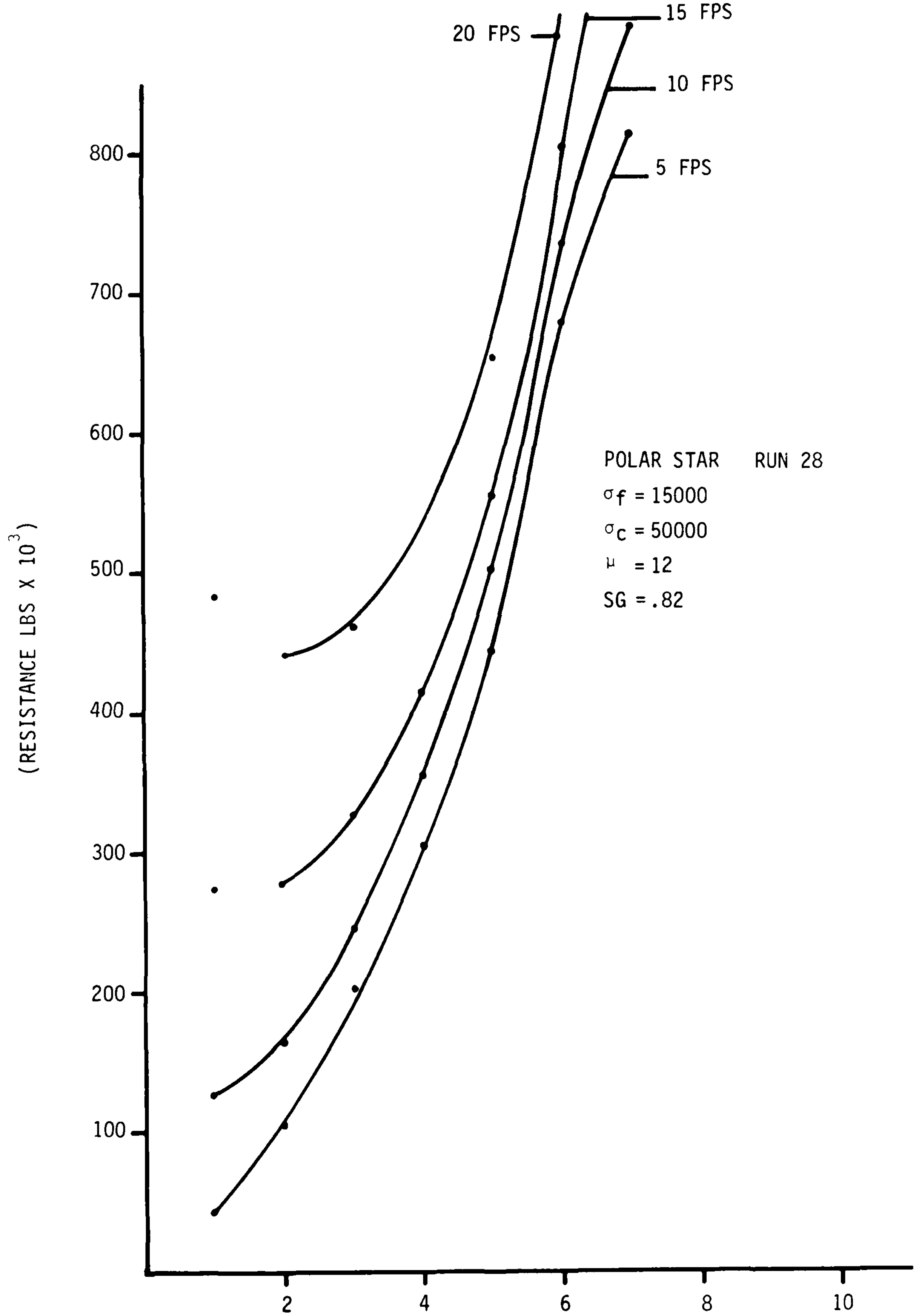
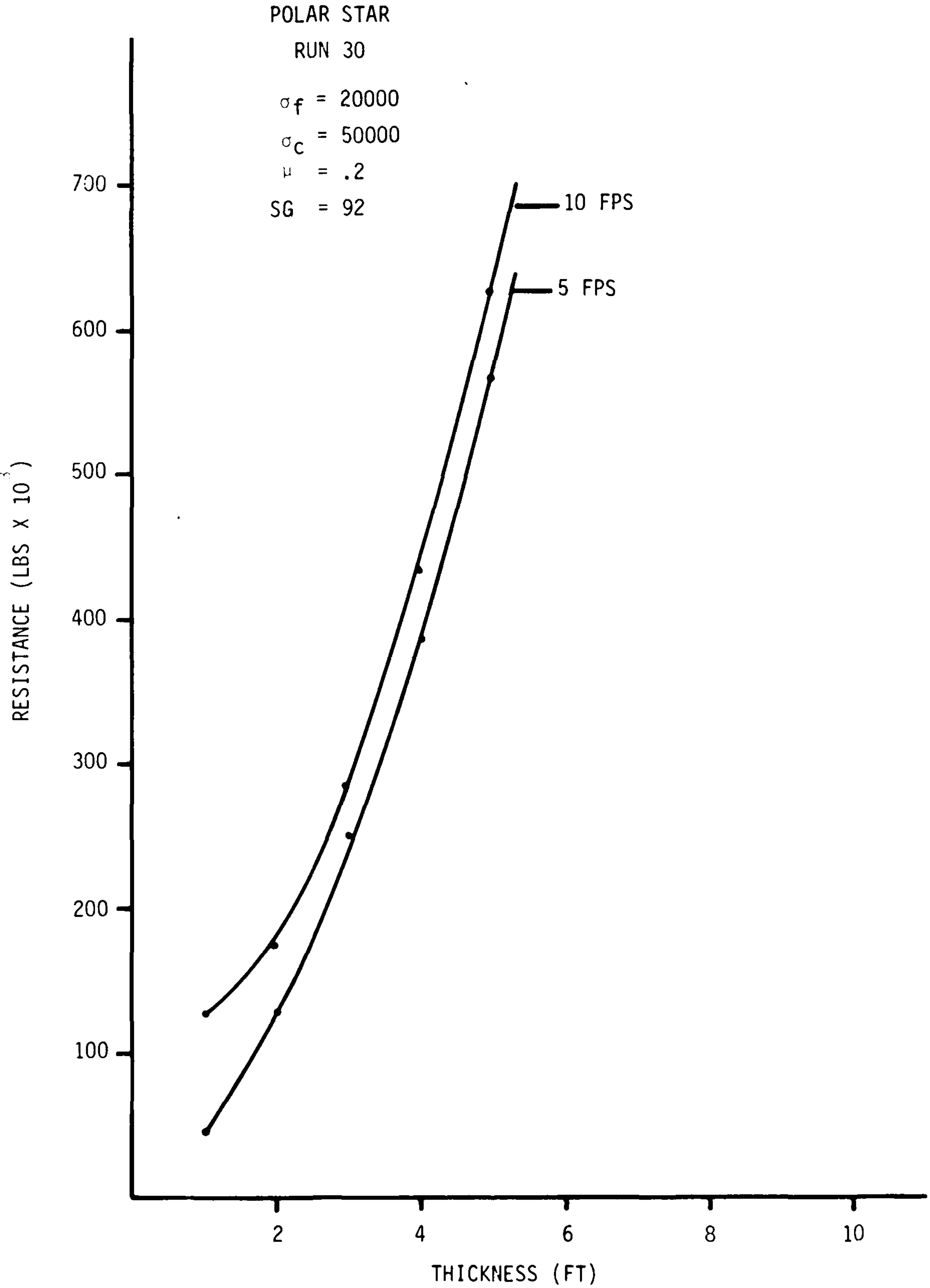

20 FPS
15 FPS
10 FPS
5 FPS
800
700
600
500
400
300
200
100
(RESISTANCE LBS X 10^3)
2
4
6
8
10
POLAR STAR RUN 28
σf = 15000
σc = 50000
μ = 12
SG = .82

Figure 17



POLAR STAR
RUN 30
$\sigma_f$ = 20000
$\sigma_c$ = 50000
$\mu$ = .2
SG = 92
10 FPS
5 FPS
700
600
500
400
300
200
100
RESISTANCE (LBS X $10^3$)
2
4
6
8
10
THICKNESS (FT)


Figure 18.

# APPENDIX B

POLAR STAR 30 ft Draft Particulars

POLAR STAR 30' particulars

LCF = 2.4 ft fsd

LWL = 363.75 ft

LCG = 3.1 ft fwd

d = 30 ft

K 6 = 28 ft

BWL = 79.33 ft

$\Delta$ = 12,200 tons - 27,328,000 lbs

BA = 14.5° = 25307 RAD

SA = .42 RAD

$F_s$ = .6

$C_W$ = .762

CM = .85

$C_p$ = .585

$KM_L$ = 379.5

$GM_L$ = 351.5

$C_b$ = .5

Water line entrace angle = 59.5°

$$WR_{30} = (.000234)(10.72+ \frac{79.33}{30})(.1833+.762)(1.652-.5)$$
$$(6.14 - (.42)^2)\ (.725-.2)(1.7180.25307)$$
$$= (.000234)(13.364)(.9453)(1.152)(5.9636)(.525)(1.457)$$
$$= .0155346$$

$$F_{BZR} = 6.64\ V\ (.0155346 \times 2.7328\text{x}10^7)^{.845}$$

$$= 6.64\ V\ (5.69617\text{x}10^4)$$

$$= 3.78226\text{x}10^5\ (V)$$

# APPENDIX C

## SAMPLE CALCULATIONS

POLAR STAR

Sample calculations of ramming capability

(28 foot draft)

Eqns:

1. $t_r = \dfrac{F_{BZR}}{100}$

2. $F_{BZR} = 6.64\ v\ (WR \times \Delta)^{0.845}$

3. $WR = 0.000234(10.72+{}^{B}/d)(0.1833+C_W)(1.652-C_b) \times (6.14-SA^2)(0.725-f_k)(1.718-BA)$

POLAR STAR

$B = 78.0$ feet
$d = 28.0$ feet
$C_W = .74$
$C_b = .49$
$SA = .420$
$f_k = .2$
$BA = .261$
$\Delta = 24{,}333{,}120$ pounds

First, the White Ratio, WR was computed:

$$WR = 0.000234(10.72 + {}^{78.0}/28.0)(0.1833 + .74)(1.652-.49) \times 6.14-(.420)^2\ (0.725-.2)(1.718-.261)$$

$$WR = .015467$$

Then $F_{BZR}$ @ speeds of 5 FPS, 10 FPS, 15 FPS, and 20 FPS were calculated in the respective order:

@5FPS: $F_{BZR} = 6.64(5)(.01546 \times 24{,}333{,}120)^{0.845} = 1{,}707{,}486.35$ pounds

@10FPS: $F_{BZR} = 6.64(10)(.01546 \times 24{,}333{,}120)^{0.845} = 3{,}414{,}972.71$ pounds

@15FPS: $F_{BZR} = 6.64(15)(.01546 \times 24{,}333{,}120)^{0.845} = 5{,}122{,}459.06$ pounds

@20FPS: $F_{BZR} = 6.64(20)(.01546 \times 24{,}333{,}120)^{0.845} = 6{,}829{,}945.42$ pounds

Finally $t_r$ was computed:

@5FPS: $t_r = \dfrac{1{,}707{,}486.35}{100} = 130''$ or $10.8'$

@10FPS $t_r = \dfrac{3{,}414{,}972.71}{100} = 184''$ or $15.4'$

@15FPS $t_r = \dfrac{5{,}122{,}459.06}{100} = 226''$ or $18.9'$

@20FPS $t_r = \frac{6,829,945}{100}$ = 261" or 21.8'

The following is a table of values computed

| v | $F_{BRZ}$ | $t_r$ in. | $t_r$ ft. |
|---|---|---|---|
| 5 | 1,707,486.35 pounds | 130 | 10.8 |
| 10 | 3,414,972.71 pounds | 184 | 15.4 |
| 15 | 5,122,459.06 pounds | 226 | 18.9 |
| 20 | 6,829,945.42 pounds | 261 | 21.8 |

The values of $t_r$ in inches were then plotted against a scale of impact velocity in FPS using speeds of 5, 10, 15, and 20 see Figure 9.

POLAR STAR

INDEX OF EXTRACTION DIFFICULTY (EQNS)

CALCULATION OF $E_t$

Extraction difficulty index = $\frac{E_t}{T_{1b}}$

1. $E_t = \frac{F_{BZR}}{\frac{a_7}{b_7}\cos\theta - \sin\theta}$

2. $a_7 = (\cos SA)\cos(BA+\theta) + f_s \sin(BA+\theta)$

3. $a_7 = (\cos SA)\sin(BA+\theta) + f_s \cos(BA+\theta)$

4. $= \frac{A_4C_3 - A_3C_4}{A_3B_4 - A_4B_3}$

5. $A_3$ =(LBP)(B)(CW)(64.2) (Constant)

6. $A_4 = \frac{F_{BZR}}{\tan BA}$

7. $B_3 = A_3$ (LCG - LCF) (Constant)

8. $B_4 = F_{BZR}\,(d-KG) + \frac{\frac{LBP}{2} - LCG}{\tan BA} - (\Delta - F_{BZR})\,(GM_1)$

9. $C_3 = F_{BZR}$

10. $C_4 = F_{BZR}\ \frac{LBP}{2} - LCG$

POLAR STAR 28' particulars

| | |
|---|---|
| LCF = 1.9 ft | BA = .261 |
| LBP = 352.0 ft | SA = .420 |
| LCG = 3.3 ft | $f_S$ = .2 x .6 |
| d = 28.0 ft | CW = .74 |
| KG 28.0 ft | $C_B$ = .49 |
| B = 78.0 ft | $KM_L$ = 378.1 ft |
| $\Delta$ = 10863(tons)x2240(lbs) = 24333120 lbs | $6M_L$=350.1 |

POLAR STAR

Index of extraction difficulty (calculations)

Calculation of $E_t$

- @ 5FPS, $F_{BZR}$ = 1,707,486.354

$$A_3 = (352.0)(78.0)(.74)(64.2) = 1,304,379.65$$

$$A_4 = \frac{1,707,486.354}{\tan(.261)} = 6392862.96$$

$$B_3 = (1304379.65)(3.3-1.9) = 1,826,131.51$$

$$B_4 = -1707486.354 \quad (28-28) + \frac{\frac{352}{2} - 3.3}{\tan(.261)} - \frac{(24,333,120-1707,486.354)}{(350.1)}$$

$$= 1707486.354\ (646.8)-7921234339$$

$$B_4 = 1104430312 \times -9,025,636,513$$

$$C_3 = 1707486.354$$

$$C_4 = (1707486.354)\ \frac{352}{2} - 3.3 = 294,882,893.3$$

$$\cdot\cdot = \frac{A_4C_3-A_3C_4}{A_3B_4-A_4B_3}$$

$$= \frac{(6,392.863)\ (1,707,486.354)-(1,304,379.65)(294,882,893)}{(1,304,379.65)(9,025,636.513)-(6,392,863)(1,826,131)}$$

$$= \frac{(1.0916\times10^{13}) - 3.846\times10^{14}}{(-1.17728\times10^{16})-1.1674\times10^{13}}$$

$$= \frac{-3.73681\times10^{14}}{-1.178\times 10^{16}} = \underline{.03172} \quad \text{Radians}$$

$$a_7 = \cos SA \cos(BA+\theta) + f_s \sin(BA+\theta)$$

$= \cos .42 \cos (.262+.03172)+.6 \sin (.262+.03172)$

$= (.913)(.957) + .6 (.289)$

$= .874 + .1734$
$= 1.0474$

$b_7 = (-\cos SA) \sin (BA+\theta)\ f_s \cos (BA+\theta)$

$= (-.913) (.2895) + .6 (.957)$

$= -.2643 + .5743 - .31$

$$\frac{a_7}{b_7} = \frac{1.0474}{.31} = 3.378$$

$$E_t = \frac{F_{BRZ}}{\frac{a_7}{b_7} \cos\theta - \sin\theta}$$

$$= \frac{1.707486\times10^6}{3.378(\cos .03172) - \sin .03172}$$

$$= \frac{1.707486\times10^6}{3.378(.99949} = \frac{1.707486\times10^6}{3.3763 - .03171}$$

$= 5.10522\times10^5$

$T_{1B} = 973\ 700$ lbs (LASKY, NSRDC Rpt, 1971)

$$\frac{E_T}{T_{IB5}} = \frac{5.10522\times10^5}{9.737\times10^5} =.52431$$

- @ 10FPS, $F_{BRZ} = 3{,}414973$ lbs

$A_3 = 1304378$

$B_3 = 1826132$

$C_3 = F_{BZR} = 3.414973$

$$A_4 = \frac{F_{BZR}}{\tan BA} = \frac{3414973}{\tan .261} = 1.27857\times10^7$$

$$B_4 = F_{BZR}\ \frac{d\text{-}KG + \frac{LB^2}{2} - LC6 - (\Delta = F_{BZR})(GM_1)}{\tan BA}$$

$= (-3414973)(646.8) - (24{,}333{,}120-3414973)(350)$

$$= (-2.2088\times10^{9}) - (7.321\times10^{9})$$

$$= -9.53 \times 10^{9}$$

$$C_4 = F_{BZR} \frac{LB^2}{2} - LCG = 3.414973\times10^{5}\ (172.7)$$

$$= 5.89765837 \times 10^{8}$$

$$\theta = \frac{(1.27857\times10^{7})(3.414973\times10^{6}) - (1.304378\times10^{6})(5.898\times10^{8})}{(1.304378\times10^{6})(-9.53\times10^{9}) - (1.2785\times10^{7})(1.826\times10^{6})}$$

$$\theta = \frac{4.4\times10^{13} - 7.7\times10^{14}}{-1.210^{16} - 2.3\times10^{13}} = \frac{-7.3\times10^{14}}{-1.2\times10^{16}}$$

$$= 061 \text{ RAD}$$

3.485

$$a_7 = (\cos .42) \cos (.262+.061) + .6 \sin (.262+.061)$$

$$= (.913)\ (.948) + .6\ (.31646)$$

$$= .8655 + 1898$$

$$= 1.055324$$

$$b_7 = (-\cos .42)\ (\sin .323) + .6\ L_r\ (.323)$$

$$= (-.913)\ (.317) + .56897$$

$$= -.2894 + .56897$$

$$= + .279549$$

$$\frac{a_7}{b_7} = \frac{1.055324}{.279549} = 3.775$$

$$E_T = \frac{3.414973}{3.775(\cos .061)} - (\sin .061) = \frac{3.414973}{3.775(.998)-.0609}$$

$$= \frac{3414973}{3.707} = \underline{921,203.2}$$

$$\frac{E_T}{T_1}\ 10 = \frac{921203}{973700} = .946$$

- @ 20FPS $\qquad F_{BZR} = 6.829\ 945\times10^{6}$ LBS

$$A_3 = 1\ 304\ 378$$

$B_3 = 1\ 826\ 132$

$C_3 = F_{BRZ} = 6.829945 \times 10^6$

$$A_4 = \frac{F_{BRZ}}{\tan BA} = \frac{6.829945 \times 10^6}{\tan .261} = 2.557 \times 10^7$$

$$B_7 = F_{BRZ} \quad \frac{d - KG + \frac{LB2}{2} - LCG}{\tan BA} - (\Delta - F_{BRZ})\, GM_L$$

$$= (-6.829945 \times 10^6)\ (646.8) - (24333120 - 6829945 \times 10^6)\ 350$$

$$= (-4.4176 \times 10^9) - (6.126 \times 10^9)$$

$$= -1.054371 \times 10^{10}$$

$$C_4 = F_{BZR} \ \frac{LBC}{2} - LCG = 6.829945 \times 10^6 (172.7)$$

$$= 1{,}179{,}531{,}502$$

$$= \frac{A_4C_3 - A_3C_4}{A_3B_4 - A_4B_3} = \frac{(2.557 \times 10^7)(6.829 \times 10^6) - (1.3 \times 10^6)\ 1.18 \times 10^9}{(1.3 \times 10^6)\ (-1.0543 \times 10^{10}) - (2.557 \times 10^7)\ (1.826 \times 10^6)}$$

$$= \frac{1.7464 \times 10^{14} - 1{,}534 \times 10^{\cdot 5}}{-1.371 \times 10^{16} - 4.669 \times 10^{13}}$$

$$= \frac{-1.359 \times 10^{15}}{-1.3756 \times 10^{16}} = .098788 \text{ RAD}$$

$$= 5.66$$

$a_7 = \cos .42 \cos (.262 + .0988) + .6 \sin (.262 \times .0988)$

$= .913\ (.936) + .6\ (.353)$

$= .8542 + .2118$

$= 1.066$

$b_7 = (-\cos .42)\ (\sin .361) + .6 \cos (.361)$

$= (-.913)\ (.353) + .56136$

$= -.32289 + .56136 =$

$= .239$

$$\frac{a_7}{b_7} = \frac{1.066}{.239} = 4.4589$$

$$E_T = \frac{6.829 \times 10^6}{4.4589\ (\cos .0988) - \sin\ (.0988)}$$

$$= \frac{6.8299 \times 10^6}{4.4589(.995) - .0986} = \frac{6.8299 \times 10^6}{4.4371 - .0986}$$

$$= 1.574 \times 10^6$$

$$\frac{E_r}{T_{1B_{20}}} = \frac{1.574 \times 10^6}{973700} = 1.6143$$

POLAR STAR

Spread angle compliment

28' WL

W.L. Entrance = 60° $\qquad \frac{E_A}{2} = 30°$

Bow 4 = 15°

$B = SAC = \arctan \frac{(\sin 15)}{\tan 30} = \tan -1\ \frac{.25881}{.57735} = \tan^{-1} .44828$

B = 24.146° = .42139 Radians .42

SA 90 - 24.146° = 65.8°

2 SA = 131.7°

30' WL

W.L. Entrance = 59.5° $\qquad \frac{E_A}{2} = 29.5°$

Bow 4 = 14.5°

$B\ (SAC) = \arctan \frac{\sin BA}{\tan \frac{E_A}{2}} = \tan^{-1} \frac{\sin 14.5}{\tan 29.5}$

$B = \arctan \frac{.2503}{.5657} = \arctan .4425$

B = 23.8715°

B = .4165 .42 Radians

SA = 90-23.87 = 66.13

2 SA = 132.26°

# APPENDIX D.

## Literature Citations

## and

## Selected Bibliography

## LITERATURE CITATIONS AND SELECTED BIBIOGRAPHY

### Literature citations


Bridewiser, D.W., (1957), "The Estimation of Tugboat Towline Pull and Effects of Types of Propelling Systems," Thesis, Webb Institute of Naval Architects.

Burrill, L.C., (1943), "Calculations of Marine Propeller Performance Characteristics," Transactions, North East Coast Institution of Engineers and Shipbuilders, London.

Buzuev, A. and Ryvlin, A., (1961), On Calculations of Icebreaker Resistance in Finely Broken Ice, Worskoj Flot 21, August.

Crago, W.A., Dix, P.J. and German, G.J., (1970), "Model Icebreaking Experiments and Their Correlation with Full Scale Data," Trans., Royal Institute of Naval Architects, April.

Day, W.G., Jr., (1968), "Powering Predictions for U.S. Coast Guard Proposed Icebreaker Represented by Models 5140, 5141 and 5142," Naval Ship Research & Development Center, Report No. P-223-H-02, January.

Day, W.G., Jr., (1969),"Analysis of Wake Survey Data for USCG Proposed Icebreaker Design Represented by Model 5169," NSRDC Report P-223-H-06, March.

Day, W.G., Jr., (1969), "Powering Predictions for U.S. Coast Guard Proposed Icebreaker Design Represented by Model 5169," NSRDC Report No. P-223-H-05, March.

Day, W.G., Jr., (1969), "Powering Predictions for USCG Proposed Icebreaker Design Represented by Model 5169," NSRDC Report No. P-223-H-07, September.

Day, W.G., Jr., (1969), "Powering Predictions for USCG Proposed Icebreaker Design Represented by Model 5169 Fitted with Altered Bossings Various Propeller Positions," NSRDC Report No. P-223-H-07, September.

Flodin, J., (1920), "Icebreakers," Marine Engineering, Vol. XXV, No. 9, September.

Gold, L.W., Block, L.D., Trofimenkof, F. and Watz, D., (1957), "Deflection of Plates on Elastic Foundation," Symposium on the Bearing Strength of Ice, Transactions, Engineering Institute of Canada, Vol. 2, No. 3, October.

Jansson, J.E., (1956), "Icebreakers and Their Design," European Shipbuilding No. 5.

Jeffreys, H. and Jeffreys, B.J., (1966), Methods of Mathematical Physics, Oxford Press, Cambridge.

Kaplan, W., (1952), Advanced Calculus, Addison-Wesley Publishing Company, Reading, Massachusetts.

Kari, A., (1921), "The Design of Icebreakers," Shipbuilding and Shipping No. 18, December.

Kasteljan, V.I., Ponznjak, I.I., and Ryvlin, A.J., (1968), Ice Resistance to Motion of a Ship, Sudostroenie, Leningrad.

Lamb, H., (1932), Hydrodynamics, 6th Ed., Dover Publications, New York.

Lewis, J.W. and Edwards, R.Y., (1971), "Methods for Predicting Icebreaking and Ice Resistance Characteristics of Icebreakers," Trans., SNAME, Vol. 79.

Lewis, J.W. and Edwards, R.Y., Jr., "Predicting Icebreaking Capabilities of Icebreakers," U.S. Coast Guard Report. (Unpublished).

Mantis, N.T., Editor, (1951), "Review of the Properties of Snow and Ice," University of Minnesota Research Report (Spire Report 4), March.

Melberg, L.C., Jr., Lewis, J.W., Edwards, R.Y., Taylor, R.G. and Voelker, R.P., (1970), "The Design of Polar Icebreakers," Transactions, Society of Naval Architects and Marine Engineers, Vol. 78.

Meyerhof, G.G., (1950), "Bearing Capacity of Floating Ice Sheets," Journal, American Society of Civil Engineers, Vol. 86.

Meyerhoff, W.K., (1970), "Added Masses of Thin Rectangular Plates Calculated from Potential Theory," Journal of Ship Research, SNAME, Vol. 14, No. 2, June.

Milano, V.R., (1960), "Notes on the Preliminary Design of Icebreakers," Thesis, Webb Institute of Naval Architecture.

Milne-Thompson, L.M., (1960), Theoretical Hydrodynamics, The MacMillan Company, New York.

Muskhelishvili, N.I., (1946), Singular Integral Equations, Institute of Mathematics, Tiflis, USSR, Moscow.

Nevel, D.E., (1961), "The Narrow Free Infinite Wedge of an Elastic Foundation," U.S. Army Cold Regions Research & Engineering Lab Research Report 79, July.

Nevel, D.E., (1968), "The General Solution of a Wedge on an Elastic Foundation," U.S. Army Cold Regions Research & Engineering Lab Research Report 247, November.

Nogid, L.M., and Fisher, A.Y., (1941), Computation of Ice Resistance to the Motion of an Icebreaker, Arctic and Antarctic Institute.

Nogid, L.M. and Dubrovin, D.V., (1962), On Viscous Resistance of Icebreakers, Sudostoenie 28, June.

Nordstrom, H.F., Edstrand, H. and Lindgren, H., (1952), "Model Tests with Icebreakers," Shipbuilding and Shiping Record, Vol. 79, June 5.

Popov, Y.N., Faddeyev, O.V., Kheysin, D.Y. and Yakovlev, A.A., (1967), Strength of Ships Sailing in Ice, Sudostroenie, Leningrad.

Pounder, E.R., (1965) Physics of Ice, Pergamon Press, Oxford, London.

Prohaska, C.W., (1947), Vibrations Verticales du Navire Bulletin de

L'Association Technique Maritime et Aeronautique.

Reisimann, H. and Lee, Y.C., (1968), "Dynamics of a Floating Ice Sheet," unknown source.

Robertson, J.M., (1965), Hydrodynamics in Theory and Application, Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Runeberg, R., (1888-1889), "On Steamers for Winter Navigation and Ice-breaking," Proceedings, Institute of Civil Engineers, London, Vol. XCVII.

Runeberg, R., (1899-1900), "Steamers for Winter Navigation and Ice-breaking," Proc., Institute of Civil Engineers, London, Vol. CXL.

Shimansky, J.A., (1938), "Conditional Standards of Ice Qualities of a Ship," Transaction, Arctic Institute of the Chief Administrator of the Northern Sea Route, Vol. 130, Leningrad.

Shultz, J.W., (1957), "The Ideal Efficiency of Optimum Propeller having Finite Hubs and Finite Number of Blades, DTMB Report 1148, July.

Simonson, D.R., (1936), "Bow Characteristics for Icebreaking," Journal of American Society of Naval Engineers, Vol. 48, No. 2, May.

Troost, L., (1950-1951), "Open-Water Test Series with Modern Propeller Forms," North East Coast Institution of Engineers and Shipbuilders, Trans., Vol 67, London.

Vossers, Ir., G., (1962), Resistance, Propulsion and Steering of Ships, Behavior of Ships in Waves, The Technical Publishing Company, Antwerp.

White, R.M., (1965), "Dynamically Developed Force at the Bow of an Ice-breaker," PhD Thesis, Massachusetts Institute of Technology.

White, R.M., (1970), "Prediction of Icebreaker Capability," Transactions, Royal Institute of Naval Architects, London, Vol. 112.

Westergaard, H.W., (1942), "Stress Concentration in Plates Loaded over Small Areas," Trans., Amer. Soc. of Civil Eng.

Westergaard, H. W., (1947), "New Formuae for Stresses in Concrete Pavements of Airfields," Trans., Amer. Soc. of Civil Eng.

Yu, Yee-Tak, (1942), "Virtual Masses and Moments of Inertia of Discs and Cylinders in Various Liquids," Jour.Appl.Phys., January.

Yu, Yee-Tak, (1945), "Virtual Masses of Rectangular Plates and Parallelepipeds in Water," Journal of Applied Physics, November.

Selected Bibliography

Aachkov, A., "An Approximate Estimate of the Static Ice Bearing Capacity of Ships," Unknown Source.

Abromowitz, (1964), Editor, Handbook of Mathematical Functions, National Bureau of Standards, U.S. Government Printing Office, Washington, D.C.

Afonasev, I.V., (1897), "Ice Breakers Design," Journal Kotlin, No. 105-120-122.

Alexandrov, A.P., Afrikantov, I.I., et al., (1958), "The Atomic Icebreaker Lenin," Proceedings, Second International Conference on the Peaceful Uses of Atomic Energy, Vol. 8, Part 1, United Nations, New York.

Ames, A., (1969), "Analog Computer Solution to the Dynamically Developed Forces at the Bow of an Icebreaker," SNAME, Chesapeake Section, March.

Assur, A., (1960), "Composition of Sea Ice and Its Tensile Strength," U.S. Army Cold Regions Research and Engineering Lab, Report 44, December.

Beer, F.P. and Johnston, E.R., Jr., (1962), Vector Mechanics for Engineers, McGraw Hill Book Company, Vols. 1 & 2, New York.

Bradley, F.D., (1951), AGB 1 and 2 - Predictions of Performance With and Without Ice Guards," DTMB Report No. 745, February.

Bronikob, A.V., (1959), "Analysis of Resistance of Cagro Ships Going Through Pack Ice," Trudy LK-1 No. 28.

Butjagin, I.P., (1966), "The Strength of Ice and of the Ice Cover," Nauka Novosibrisk.

Butkovich, T.R., (1954), "Ultimate Strength of Ice," U.S. Army Snow, Ice and Permafrost Research Establishment, Research Paper 11, December.

Butkovich, T.R., (1956), "Strength Studies for Sea Ice," U.S. Army Snow, Ice and Permafrost Research Establishment, Research Report 20, October.

Comstock, J., (1967), Editor, Principals of Naval Architecture, (Revised), SNAME.

Corlett, E.C.B. and Snaith, G.R., (1964), "Some Aspects of Icebreaker Design," Trans., Roy. Inst. of Nav. Arch., March.

Dauydov, V.V., (1938), "Theoretical Investigation on Impact of a Ship with an Ice Floe," Problem of the Arctic and Antarctic 5-6.

Day, W.G., Jr., (1967), "Effective Horsepower Predictions for USCG Proposed Icebreaker Designs Represented by Models 5040, 5141, 5142," NSRDC Report No. P-223-H-01, August.

Day, W.G., Jr., (1968), "Effective Horsepower Predictions for U.S. Coast Guard Proposed Icebreaker Design Represented by Model 5169," NSRDC Report No. P-223-H-03, June.

Day, W.G., Jr., (1968), "Flow Observations of Model 5169 Representing USCG Proposed Icebreaker Design," NSRDC Report P-223-H-04, September.

Dayton, R.B., (1968), "Polar Icebreaker Preliminary Structured Design and Special Studies," ConSulTec Report No. 006, August.

De Haan, B., (1939), Nouvelles Tables D'Integrales Definies, G.E. Stechert & Company, New York.

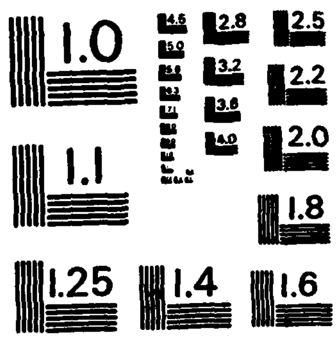
AD-A121 528 TEST AND EVALUATION OF CGC POLAR STAR WAGB 10 VOLUME III BACKGROUND(U) NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY NSTL STATION MS J P WELSH SEP 78 2/2

UNCLASSIFIED NORDA-22-VOL-3 MIPR-Z-51100-8-0003 F/G 13/10 NL

END

FILMED

DTIC




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Dix, P.J., (1966), "Model Tests on a Wind Class Icebreaker for the U.S. Coast Guard," Westland Aircraft (Saunders-Roe Division) Report X/0/865.

Dix, P.J., (1966), "Model Tests of a Modified Wind Class Icebreaker for the U.S. Coast Guard," Westland Aircraft (Saunders-Roe Division) Report X/0/898.

Dix, P.J., (1967), "Model Tests of a Triple-Screw Icebreaker for the U.S. Coast Guard, Part 1 - Resistance and Propulsion Tests," Westland Aircraft (Saunders-Roe Division) Report X/0/929, February.

Dix, P.J., (1967), "Model Tests of a Tripe-Screw Icebreaker for the U.S. Coast Guard, Part 11 - Icebreaking Tests," Westland Aircraft (Saunders-Roe Division) Report X/0/964, September.

Dremljug, V.V. and Laktionov, D.F., (1944), "An Analysis of Ship Speed in Arctic Ice," Problems of the Arctic and Antarctic No.1 .

Du Brovin, O.V., (1966), "Calculation of Broken Ice Resistance Based on Model Testing," Trudy LK-1 No. 2.

Durand, W.F., Editor, (1963), Aerodynamic Theory, Dover Publications, New York.

Edwards, R.Y., (1966), "Model Tests on a Wind Class Icebreaker," U.S. Coast Guard Report X/0/865.

Edwards, R.Y., (1967) "U.S. Coast Guard Evaluation of the Alexbow Ice-breaking Device," U.S. Coast Guard Report.

Estrada, H., Jr., and Ward, J. R., (1968), "Forces Exerted by Ice on Ships," SNAME Journal of Ship Research, Vol. 12, No. 4, December.

Evans, D.V., and Davies, T.V., (1968), "Wave Ice Interaction," Davidson Laboratory R-1313, Stevens Inst. of Technology, August.

Ferris, L.W., (1959), "The Proportions and Form of Icebreakers," Trans., SNAME, Vol. 67.

Fey, E., Pilkey, W. and Estes, P., (1968), "Structural Analysis of Polar Icebreaker Bows," ITT Research Institute Report 56127, November.

Fisher, R.E., (1950), "AGB1 and 2, Predictions of Performance with and without Ice Guards," DTMB Report No. 034, September.

Gakkel, J., (1937), "Evaluation of Ice Penetrability on the Northern Sea Route During 1933-1935,: Problems of the Arctic and Antarctic No. 1.

Genalis, P., (1967), "Three-Dimensional Stresses in Icebreaker Primary Structures," MIT Report No. 67-7, Massachusetts Institute of Technology, May.

German, J.G., (1959), "Design and Construction of Icebreakers," Trans., SNAME, Vol. 67.

German, J.G., Collins, C.F. and Webster, A.R., (1971), "Some Considerations in the Design of Polar Icebreakers," SNAME, New York Metropolitan Section, 23 February.

Gouljaeff, N., (1935), "Icebreakers," The Shipbuilder and Marine Engine Builder, March.

Gover, S.C., (1949), "Rolling Characteristics of Model 3705 Representing USS Buiton Island," DTMB Report No. 685, February.

Grim, O., "About Icebreaking," Unknown source.

Grim, O. and Hattendorf., "Icebreaking Tests," Hamburg Schiffversuchsanstalt Report 1174.

Groesberg, S.W., (1968), Advanced Mechanics, John Wiley & Sons, Inc., New York.

Hendrickson, G. and Rowland, R., (1965), "Strength Studies on Antarctic Sea Ice," U.S. Army Cold Regions Research and Engineering Laboratory Technical Report 157, July.

Henry, C.J., (1968), "Wave-Ice Interaction," Davidson Laboratory Report 1314, Stevens Institute of Technology, December.

Hildebrand, F.B., (1952), Methods of Applied Mathematics, Prentice Hall, Englewood Cliffs, New Jersey.

Hildebrand, F.B.. (1962), Advanced Calculus for Applications, Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Hill, R.C., and Coburn, S.C., (1952), "A Design Study for a Polar Icebreaker," Thesis, MIT.

Hinterthan, W.B. and Yeh, H.Y., (1958), "Prediction of Power Performance for AGB-1 Class Fitted with Kort Nozzles as Ice Guards From Tests with Model 3705-1," DTMB Report No. 1197, April.

Icheisin, D.E., (1961), "Determination and Appraisal of the Structural Strength of Ships Designed for Navigation in Ice by Recalculated Data from the Prototype," Sudostroenie.

Ignatyev, M.A., (1964), "Determination of Ice Loads Encountered by Ship Propeller Blades," Problems of the Arctic and Antarctic, No. 15, Leningrad.

Illingworth, F., (1962), "The Polar Fleets," The Shipping World, 10 January.

Jansson, J.E., (1956), "Icebreakers and Their Design," European Shipbuilding, No. 5.

Javovlev, M.J., (1967), "An Approximate Evaluation of the Ice Penetrativeness of Icebreakers," GPI.

Johnson, H.F., (1946), "Development of Icebreaking Vessels in the U.S. Coast Guard," Trans., SNAME, Vol. 54.

Jordan, R.C., (1955), "Friction on Snow and Ice," University of Minnesota Research Report, June.

Kampke, E., (1959), Differentialglerchungen, Chelsea Publishing Company, New York.

Kari, A., (1938), Design and Cost Estimating of Merchant and Passenger Ships, The Technical Press, Ltd., London.

Kasteljan , V.I., (1960), "Approximate Determination of Forces for Breaking the Ice Cover," Problems of the Arctic and Antarctic No. 5.

Kasteljan , V.I. and Ryvlin, A.J., (1960), "The Influence of Natural Characteristics of Continuous Ice in Evaluation of the Penetrability by an Icebreaker," Problems of the Arctic and Antarctic No. 5.

Kasteljan , V.I., (1962), "The Study of Resistances of Continuous Ice to Ship Motion in Model Experiments," Thesis, Arctic and Antarctic Institute, Leningrad.

Kasteljan , V.I. and Ryvlin, A.J., (1966), "The Influence of Natural Characteristics of Solid Ice in Evaluation of its Resistance to Icebreaker Passage," Problems of the Arctic and Antarctic No. 22.

Kassell, B.M., (1951), "Russia's Icebreakers," Journal of ASNE, Vol. 63, No. 1, February.

Kneisin, D.Y., (1967), Dynamics of the Ice Cover, Translation from the Russian GIDROMETEOROKOGICHESKOE, Leningrad.

Khejsin, D.E., (1961), "Contact Pressures Resulting From Impact of the Ice Barge on Ice," Problems of the Arctic and Antarctic No. 8.

Kiesling, E.W., (1967), "Structural Analysis Including Thermal Effects in Icebreakers," Southwest Research Institute Report, June.

Kochin, N.J., Kibel, I.A. and Rose, N.W., (1954), Theoretische Hyromechanik, Berlin.

Korznavin, K.N. and Ptukhin, F.I., (1966), "Evaluation of the Compressive Strength of Ice Under Short Term Rapidly Increasing Load," U.S. Army Foreign Science and Technology Center, Tech. Translation HT-23-188-68.

Lank, R.B., (1947), "The Influence of Arctic Operations on Future Ship Designs," Journ. ASNE, Vol. 59, No. 2, May.

Lank, S.W. and Oakley, O.H., (1959), "Application of Nuclear Power to Icebreakers," Trans., SNAME, Vol. 67.

Lewis, J.A., (1966), "Report on the Acceleration Performance of Icebreakers," U.S. Coast Guard Report, December.

Lewis, J.W., Scoville, F.W. and Lecourt, E.J., (1967), "Icebreaker Propulsion System Simulation, Phase 1 - Simulation of USCG Glacier," U.S. Coast Guard Report, September.

Lewis, J.W., Lecourt, E.J. and Scoville, F.W., (1967), "Icebreaker Propulsion System Simulation, Phase 111 - Propulsion System Behavior during Propeller Ice Interactions," U.S. Coast Guard Report, December.

Lewis, J.W., (1968), "Ship Design and Maintenance Computer Program - TORK, Ice Load Torque Calculations," U.S. Coast Guard Report No. ENE-10, April.

Lewis, J.W., (1968), "Ship Design and Maintenance Computer Program Icebreaker Propulsion System Simulation (Diesel-Electric)," U.S. Coast Guard Report ENE-11, May.

Lewis, J.W. and Lecourt, E.J., (1968), "Icebreaker Propulsion System Simulation, Phase IV - The Design and Predicted Performance of a Propulsion System for the M-13 Icebreaker," U.S. Coast Guard Report, August.

Lewis, J.W., (1969), "Some Aspects of the Design of Diesel Electric Icebreaker Propulsion Systems," Jour. ASNE, April.

Lloyd's Register of Shipping: (1967), "Structural Guidance Study for Large Polar Icebreakers," R&TA Report No. 5047, March.

Lloyd's Register of Shipping: (1967), "Structural Guidance Study for Large Polar Icebreakers," R&TA Report No. 5048, April.

Lloyd's Register of Shipping: (1967), "Structural Guidance Study in Large Polar Icebreakers," R&TA Report No. 5051.

Lloyd's Register of Shipping: (1967), Large Plar Icebreaker for U.S. Coast Guard, R&TA Report No. 5054, November.

Loukakis, T.A., "Seakeeping Tests of the M-5 Icebreaker," MIT Report No. T-67-1, Mass. Inst. of Tech.

Marris, A.W. and Stonekling, C.E., (1967), Advanced Dynamics, McGraw Hill Book Company, New York.

Maslov, A.I., (1937), "Evaluation of External Forces Acting on a Ship Hull in Ice," Trudy VNITOSS, Vol. 11, No. 3.

Mathews, S.T., (1956), "An Investigation into Icebreaking," SNAME, Eastern Canadian Section.

Mathews, F.W., (1959), "Stability and Control of HMCS LABRADOR," Trans., SNAME, Vol. 67.

McCuskey, S.W., (1962), An Introduction to Advanced Dynamics, Addison-Wesley Publishing Company, Reading, Massachusetts.

McDonald, F.A., (1966), "Our Icebreakers are Not Good Enough," U.S. Naval Institute Proceedings, Vol. 92, No. 2.

McLachlan, N.W., (1955), Bessel Functions for Engineers, Clarendon Press, Oxford.

Mendl, W.V., "Icebreakers," Shipbuilder and Marine Engine Builder, Vol. 45.

Milano, V.R., (1962), "Notes on Icebreaker Design," Journal ASNE, February.

Milano, V.R., (1962), "Preliminary Vessel Estimates in Icebreaker Design," Jour. ASNE, August.

Milne, W.J., (1951), "Icebreaking Vessel," Thesis, Mass. Inst. of Tech.

M. Rosenblatt & Son Inc., (1967), "Icebreaker Feasibility Design-Computer Program, MR&S Report BSD-1748-1, April.

Munro, Smith R., (1941), "The Design of Icebreakers," Shipbuilding and Shipping Record, Vol. 57, 6 February.

National Research Council of Canada: (1958), "The Bearing Strength of Ice," Technical Memorandum No. 56, Transactions, Engineering Institute of Canada, Vol. 2, No. 3, October.

Nazarov, V.S., (1941), Ice Properties and Its Penetrability, Morsicoj Sbornik Nos. 11 and 12.

Nevel, D.E., (1968), "Time Dependent Deflection of a Floating Ice Sheet," U.S. Army Cold Regions Research & Engineering Lab.

Nevel, D.E., (1958), "The Narrow Infinite Wedge on an Elastic Foundation," U.S. Army Snow, Inc. and Permafrost Research Establishment, Technical Report 56, July.

Nevel, D.E., (1970), "Concentrated Loads on Plates," U.S. Army Cold Regions Research & Engineering Lab, Research Report 265, March.

Nevel, D.E., (1965), "A Semi-Infinite Plate on an Elastic Foundation," U.S. Army Cold Regions Res. & Engr'g Lab, March.

Nevel, D.E., (1967), "Ice Breaker and Ice Modeling," U.S. Army Cold Regions Res. & Engr'g Lab, February.

Nevel, D.E., (1967), "Ice Breaker Simulation," U.S. Army Cold Regions Res. & Engr'g Lab, August.

Nevel, D.E., (1968), "Vibration of a Floating Ice Sheet," U.S. Army Cold Regions Res. & Engr'g Lab, Technical Note, September.

Nogid, L.M., (1959), "The Resistance to the Forward Motion of an Icebreaker in Pack Ice Based on Model Data - 1949-1951," BSRA Translation #2522, Transactions, Leningrad Shipbuilding Institute No. 29.

Nogid, L.M., (1959), "Model Representation of a Ship Going Through a Continuous Ice Field or Pack," Transactions of the Leningrad Shipbuilding Institute, No. 28.

Nogid, L.M., (1962), "On Impact of a Ship with an Ice Floe," Trudy Leningrad Koraslestr Institute No. 26.

Noonan, E.F., et al., (1967), "Integrated Vibration Study for a New Design Polar Icebreaker," November.

Nordstrom, H.F., Edstrand, H. and Lindgren, H., (1952), "Model Tests with Icebreakers," Shipbuilding and Shipping Record, Vol. 79, June 5.

Nowacki, H., Arbel, J. and Chopra, H.J., (1966), "Study of Twin and Triple Screw Systems for Icebreakers," ORA Project Report 08121, University of

Michigan, College of Engineering, September.

NUS Corporation and Hydronautics Inc., (1966), "Icebreaker Propulsion Systems Feasibility Study, Phase 1 - Presentation," NUS Report 323A, November.

NUS Corporation and Hydronautics Inc., (1966), "Icebreaker Propulsion Systems Feasibility Study - Ships Study," NUS Report 323, Vol. 1, November.

NUS Corporation and Hydronautics Inc., (1966), "Icebreaker Propulsion Systems Feasibility Study, Nuclear Propulsion Systems," NUS Report 323, Vol. 11, November.

NUS Corporation and Hydronautics Inc., (1966), "Icebreaker Propulsion Systems Feasibility Study, Conventional Propulsion Systems," NUS Report 323, Vol. 111, November.

NUS Corporation and Hydronautics Inc., (1967), "Icebreaker Propulsion Systems Feasibility Study, Nuclear Programs Implications," NUS Report 323, Vol. IV, January.

NUS Corporation and Hydronautics Inc., (1967), "Icebreaker Propulsion Systems Feasibility Study, Mission Sensitivity Analysis," NUS Report 323, Vol. 11, February.

NUS Corporation and Hydronautics Inc., (1967), "Icebreaker Propulsion Systems Feasibility Study, Electric Propulsion and Ship Service Electric Systems," NUS Report 323, Vol. V, February.

NUS Corporation and Hydronautics Inc., (1967), "Icebreaker Propulsion Systems Feasibility Study, Reference Plant Design Description," NUS Report 323, Vol. VIA, March.

NUS Corporation and Hydronautics Inc., (1968), "Nuclear Icebreaker Feasibility Summary," NUS Report 369, May.

Ormondroyd, J., (1950), "Investigation of Structural Stress in Ice-breaking Vessels," University of Michigan, June.

Ormondroyd, J., (1947), "Studies of Forces which Act Upon a Vessel Engaged in Breaking Ice and Reactions Occurring in the Hull Girder of Such a Vessel," University of Michigan, September.

Peterson, R. A. and Chabot, P. L., (1968), "A Survey of Antarctic Ice Data," Naval Oceanographic Office, Report IR NO. 68-112, December.

Petrov, L.E., (1955), Navigation in Ice, Morskoj Transport.

Petrov, E.J., (1965), "Determination of the Forces of Retention in Wedging of an Icebreaker," Problem of the Arctic and Antarctic No. 20.

Petrov, E.J., (1966), "Determination of Hull Emergence during the Impact Period of Icebreaker Work," Problems of the Arctic and Antarctic No. 29.

Pierson, J.D., (1950), "The Penetration of a Fluid Surface by a Wedge," ETT Report #381, Davidson Laboratory, S.I. T., July.

Pierson, J.D., "On the Pressure Distribution in a Wedge Penetrating a Fluid Surface, ETT Report 336, Davidson Laboratory, S.I.T.

Popov, J.N., (1955), "On the Problems of Impact of a Ship with an Ice Floe," Trudy Leningrad Korablestr Institute No. 15.

Porricelli, J.D., (1967), "Turning Characteristics of U.S. Coast Guard Icebreaker M-5," University of Michigan, College of Engineering, June.

Poznyak, I.I., Popov, Y.N., Sukhurukov, A.Y., (1960), "Research in the Field of Icebreakers," Problems of the Arctic and Antarctic No. 4.

Rachkov, A., (1966), "An Approximate Estimate of the Static Icebreaking Capacity of Ships," Morskoi Flot, Vol. 26, No. 10, October.

Ratmanov, G.E., (1940), "The Experience with Direct Observations of Ice Penetrability," Trudy, ANII Vol. 137.

Richardson, C., (1959), "Model Studies of the Force Systems on Icebreakers during Icebreaking Operations," Project Study No. 299, University of California, September.

Richardson, C., (1966), "Similitude Correlations for Modeling Icebreaker Operations," Journ. ASNE, December.

Richardson, C., (1969), "A Model Study of Icebreaker Operation," Journ. ASNE, Vol. 18, No. 5, October.

Richmond, C.A., et al., (1970), "Development of Sea Transporation," Journal of the Marine Technological Society.

Ritger, P.D., and Rose, N.J., (1968), Differential Equations With Applications, McGraw Hill Book Company, New York.

Ryvlin, N.J., (1963), "A Method for Determination of Penetrativeness of a Ship in Broken Ice," Dissertation Abstract, AANII.

Sammis, G.G., (1967), "Underwater Photography of an Operating Icebreaker," TRG Division, Control Data Corporation, Report No. 0120A-1, May.

Scoville, F.W., Lewis, J.W., and Lecourt, E.J., (1967), "Icebreaker Propulsion Systems Simulation, Phase II - Dynamics of AD-DC Propulsion Systems," U.S. Coast Guard Report, October.

Simons, R.L., (1935), "Icebreakers," U.S. Naval Institute Proceedings, January.

Smirnov, V.I., (1960), "Prediction of Icebreaker Speed through Solid Ice," Problems of the Arctic and Antartic No. 5.

Smith, N., (1969), "Determining the Dynamic Properties of Snow and Ice by Forced Valuation," U.S. Army Cold Regions R&E Laboratory, TR-216, June.

Suarez, A., (1967), "Tactical and Spiral Maneuver Model Tests of a 368-ft Polar Ice Breaker," DL LR-1212, June.

Swan, H.F., (1899), "Icebreakers," Transactions, Royal Institute of Naval Architects, Vol. 41, London.

Szebehely, V.G., (1952), "Hydrodynamics of Slamming of Ships," TMB Report 823, U.S. Navy Ship Research and Development Center, Washington, D.C., July.

Tarshis, M.K., Ice Loads Acting on Ships, Unknown Source.

Tarshis, M.K., (1957), Ice Resistance of Ships, Trudy Murmanskoko Morekhodnogo Uchkishcha, Morskoj Transport No. 1.

Taylor, N.M., (1967), "The United States Requirements for Polar Icebreakers," Vitro Laboratories Tech. Report No. 0203P.01-2A, February.

Thiele, E.H., (1959), "Technical Aspects of Icebreaker Operation," Trans., SNAME, Vol. 67.

Timoshenko, S., (1940), Theory of Plates and Shells, McGraw Hill Book Co., New York.

Timoshenko, S., and Young, D.H., (1945), Theory of Structures, McGraw Hill Book Company, New York.

Todd, M.H., (1954), "Slamming Due to Pure Pitching Motion," TMB Report 883, U.S. Navy Ship Research & Development Center, Wash., D.C., February.

Vance, G.P., (1968), "Model Testing in Ice," Jour.ASNE, April.

Vinogradov, I.V., (1946), Vessels In Arctic Navigation, Library of Congress (vm) 451.25, Russia.

Vinogradov, I.V., (1958), The Icebreaker, Schiff and Hafen, January and March.

Vinogradov, I.V., (1962), "The Study of Resistance of Continuous Ice to Ship Motion in Model Experiments," Thesis, Arctic and Antartic Institute, Leningrad.

Voelker, R.P., and Koch, E., (1968), "The Design of a Ship's Control Space in Polar Icebreakers," U.S. Coast Guard Report, May.

Wagner, H., (1931), "Landing of Sea Planes," Tech. Memorandum #622, National Advisory Committee for Aeronautics," Washington, D.C., May.

Watson, H., (1959), "Operation of Department of Transport Icebreakers," Trans., SNAME, Vol. 67.

White, R.M. and Vance, G.P., (1967) "Icebreaker Model Tests," Journal ASNE, August.

Zabotkin, N.A., (1951), "Impact of an Icebreaker Against an Ice Field and Its Riding Up onto the Ice," Trudy, Leningrad Korablester Institute No. 9.

Zyler, B.V., (1950), "Ice Pressure on an inclined Ice Cutter," Trans. Moscow Institute of Railroad Transportation Engineering of the Order of Lenin, Vol. 74.

Anon.: (1941), "Icebreakers," Shipbuilding and Shipping Record, Vol. 58, 20 November.

Annon.: (1945), "Icebreaker Design," Marine Engineering and Shipping Review, Vol. 50, April.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>NORDA Report 22 | 2. GOVT ACCESSION NO.<br>A121528 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Test and Evaluation of CGC POLAR STAR, WAGB 10 | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>James P. Welsh, Jr. | | 8. CONTRACT OR GRANT NUMBER(s)<br>MIPR Z-51100-8-0003 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Naval Ocean Research & Development Activity<br>NSTL Station, MS 39529 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>980101 Prog. Ele<br>933227 Work Unit |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>U.S. Coast Guard Research & Development Center<br>Avery Pt., Groton, CT 06340 | | 12. REPORT DATE<br>September 1978 |
| | | 13. NUMBER OF PAGES<br>639 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE<br>None |

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Unlimited

18. SUPPLEMENTARY NOTES

Report consists of 4 (four) volumes

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Icebreaker
Ice Testing
Ship Test
Arctic ice
Antarctic ice

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

CGC POLAR STAR is the first of a new class of American icebreakers built for and operated by the U.S. Coast Guard. The vessel's design incorporates many new and sophisticated systems not found on earlier icebreakers.

The primary objective of the test and evaluation program was to examine the performance characteristics under actual polar operations. Two field trials were conducted. The first in the Arctic and the second in the Antarctic. During these field trials approximately 120 individual parameters were

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

measured and recorded on magnetic tape. Additionally, the physical properties of the sea ice in which the ship was operating were measured.

Documentation of the complete program including preliminary screening of the data has been accomplished by NORDA under contract to the Coast Guard Research and Development Center. The documentation consists of the following four volumes: I. Antarctic Trials, II. Test Plans, III. Background, and IV. Instrumentation Manual.

END

FILMED

1-83

DTIC